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Industry, Energy, and Transportation: Impacts and Adaptation

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CONTENTS

Executive Summary 367

11.1. Introduction 369
- 11.1.1. Adapting to Climate Change 369
- 11.1.2. Adaptation and Mitigation 370

11.2. Characteristics and Sensitivities of the Sectors 370

11.3. Overview of the Literature 372
- 11.3.1. Methods 372
- 11.3.2. Biases in the Literature 372
- 11.3.3. Framework for the Review 374

11.4. Economic Activity with Climate-Sensitive Markets 376
- 11.4.1. Energy Demand 376
  - 11.4.1.1. Energy Demand for Space Heating and Air Conditioning 376
  - 11.4.1.2. Energy Demand in Agriculture 378
- 11.4.2. Space Heating/Air Conditioning Equipment 378
- 11.4.3. Construction 378
  - 11.4.3.1. Climate Sensitivities 378
  - 11.4.3.2. Adaptation to Sea-Level Rise 379
  - 11.4.3.3. Building Design and Climate Change 379
- 11.4.4. Demand for Transportation Infrastructure and Services 379
- 11.4.5. Other Market Impacts 380

11.5. Economic Activity Sensitive to Climate 381
- 11.5.1. Construction 381
- 11.5.2. Transportation Operations and Infrastructure 381
  - 11.5.2.1. Transportation Operations 381
  - 11.5.2.2. Sea-Level Rise and Coastal Infrastructure 382
  - 11.5.2.3. Other Infrastructure 382
- 11.5.3. Energy Transportation and Transmission 382
- 11.5.4. Offshore Oil and Gas 382
- 11.5.5. Thermal Power Generation 383
- 11.5.6. Water Availability for Industry 383
- 11.5.7. Pollution Control and Climate Change 383
- 11.5.8. Coastally Sited Industry 384
- 11.5.9. Tourism and Recreation 384

11.6. Economic Activity Dependent on Climate-Sensitive Resources 385
- 11.6.1. Agroindustry 385
  - 11.6.1.1. Economic Impacts on the Food Industry 385
  - 11.6.1.2. Industry Dependent on Forestry 388
  - 11.6.1.3. Textiles 389
- 11.6.2. Biomass 390
  - 11.6.2.1. Impacts of Climate Change on Domestic Biomass 390
  - 11.6.2.2. Impacts of Climate Change on Industrial Biomass 390
  - 11.6.2.3. Adaptation to Gradual Change 391
  - 11.6.2.4. Adaptation to Extreme Events 391
- 11.6.3. Renewable Energy 391
  - 11.6.3.1. Impacts on Resources 391
  - 11.6.3.2. Impacts on the Value of Resources 393
  - 11.6.3.3. Impacts on Performance 393

11.7. Need for Future Assessments 393

References 394

EXECUTIVE SUMMARY

Introduction

Climate change will have *direct* impacts on economic activity in the industry, energy, and transportation sectors; impacts on *markets for goods and services;* and impacts on the *natural resources* on which economic activity depends. Activities directly sensitive to climate include construction, transportation, offshore oil and gas production, manufacturing dependent on water, tourism and recreation, and industry that is located in coastal zones and permafrost regions. Activities with markets sensitive to climate include electricity and fossil fuel production for space heating and air conditioning, construction activity associated with coastal defenses, and transportation. Activities dependent on climate-sensitive resources include agroindustries (food/drink, forestry-related activity, and textiles), biomass production, and other renewable energy production.

The overall effect of climate change in the industry, energy, and transportation sectors will be the aggregation of a large number of varied individual impacts. The interconnectedness of economic activity means that many of the impacts are indirect and will be transmitted by transactions within and between economic sectors. Energy, water, and agricultural products in particular will transmit climate sensitivity through the economic system.

Findings

There is generally a high level of confidence concerning the sensitivities of specific activities to given changes in given climate variables. Reliable climate scenarios describing climate variables, apart from temperature, do not exist at the regional level, however. There is, therefore, a low level of confidence about the direction as well as the magnitude of some climate impacts when uncertainties about climate change at the regional level are taken into account.

Certain components of the industry/energy/transportation sectors display a greater degree of sensitivity to climate than does the sector as a whole.

- There is a high level of confidence that agroindustries that depend on products such as grain, sugar, and rubber are vulnerable to changes in precipitation patterns and the frequency and intensity of extreme weather events. Agroindustry is of relatively greater significance in many developing countries where, together with agriculture, it constitutes the bulk of economic activity. In areas with low agricultural productivity and high population densities, climate change could have a significant effect on the production of biomass (i.e., living matter that can be burned to meet energy needs).
- There is a high level of confidence that hydroelectric production will be influenced by changes in precipitation and water availability. There is low confidence concerning whether these changes will be beneficial or otherwise because much depends on the relationship between seasonal patterns of precipitation and electricity demand in specific regions.
- It is certain that higher temperatures resulting from climate change will reduce energy needs for space heating and increase those for air conditioning. There is a low level of confidence concerning the balance between these changes. For example, one study of the United States concluded that energy needs could fall by 11% with a 1°C rise in temperature. Another concluded that electricity demand would increase by 4–6% with a rise of 3.7°C.
- There is a high level of confidence that sea-level rise will increase the cost of protecting transportation infrastructure and industrial plants located in coastal regions. Coastal protection will provide a market opportunity for the construction industry.
- There is a high level of confidence that climate change will increase the vulnerability of infrastructures located in permafrost regions.
- There is a high level of confidence that skiing seasons will shorten with consequent impacts on some local economies. There is also a high level of confidence that sea-level rise will affect tourism in beach resort areas.

Although the energy, industry, and transportation sectors are of great economic importance, the climate sensitivity of most activities is low relative to that of agriculture and natural ecosystems, while the capacity for autonomous adaptation is high, as long as climate change takes place gradually. The lifetimes of most assets are short compared to projected time scales for climate change. Consumer goods, motor vehicles, and heating and cooling systems will be replaced several times over the next half century. Even medium-life assets such as industrial plants, oil and gas pipelines, and conventional power stations are likely to be completely replaced, though there will be less opportunity for adaptation. Additional difficulties and costs could arise with long-lived assets, including some renewable energy projects and residential buildings.

The technological capacity to adapt to climate change will be realized only if the necessary information is available and the institutional and financial capacity to manage change exists. Autonomous adaptation cannot be relied upon, and governments may have to set a suitable policy framework, disseminate information about climate change, and act directly in relation to vulnerable infrastructures. Many developing countries are dependent on single crops or on fishing and therefore are economically vulnerable to climate change through impacts on agroindustry. Diversifying economic activity could be an important precautionary response that would facilitate successful adaptation.

Context

In comparison with natural ecosystems and agriculture, little work has been carried out on impacts and adaptation in the industry, energy, and transportation sectors. The literature on adaptation and adaptation policies is particularly sparse. This partly reflects the perception that climate sensitivity is low and that adaptation could take place autonomously. Much of the attention of the policy and research communities has been focused on mitigation actions in the energy and transportation sectors.

Research on climate impacts has focused largely on developed rather than developing countries, even though the latter have less diversified economies that may be more vulnerable to climate change. Within the developed countries, work has focused on a small number of impacts, notably the possible effects of climate change on energy demand. This may reflect the availability of research tools as much as priority-setting.

Further research would be assisted by the generation of climate scenarios covering a fuller range of variables at the regional level. There is a need to broaden the scope of work to cover a wider range of activities (for example, agroindustry) and a wider range of countries, especially developing countries. Studies that begin to draw out the interdependence of economic activities in relation to climate would be particularly helpful.

11.1. Introduction

This chapter reviews literature addressing the potential impacts of climate change on the energy, industry, and transportation sectors and the associated capacity for adaptation. The chapter begins by considering broad issues relating to impacts and adaptation in the three sectors. It moves on to a more precise definition of the sectors, identifying their economic importance and the more important climate sensitivities. There follows a general overview of the different types of studies that have been conducted and the range of methodologies that have been used. The largest part of the chapter is devoted to a detailed review of this literature. For this purpose, activity is classified according to three types of climate sensitivity: activities with markets that are sensitive to climate, activities and processes that may be directly affected by climate change, and activities that are dependent on climate-sensitive resources.

A wide range of individuals and organizations will be affected directly or indirectly by climate change in the energy, industry, and transportation sectors. These include:

- Individuals in their role as consumers or citizens
- Businesses, operating over a wide range of scale and technological sophistication, which may be privately owned or run as state enterprises
- Policymakers concerned with land-use planning and the development of transportation, energy, or industrial infrastructures that may be affected by climate change
- Policymakers making high-level decisions about the adequacy of policies to deal with climate change and the appropriate balance between adaptation and mitigation strategies.

Because global warming and other climatic changes will result from the impact of past economic activity, the first three groups will be affected by climate change independently of current and future mitigation actions. This chapter is aimed at the needs of these groups. The needs of policymakers who are responsible for balancing mitigation and adaptation strategies are addressed, especially in Chapter 6, *The Social Costs of Climate Change: Greenhouse Damage and the Benefits of Control*, and Chapter 7, *A Generic Assessment of Response Options*, in the IPCC Working Group III volume; Nordhaus (1993) also addresses these issues.

11.1.1. Adapting to Climate Change

Adaptation to a changed climate may occur through the actions of individuals and enterprises, or it may be stimulated by policies promoted by those concerned with planning and infrastructure development. "Autonomous adaptation," i.e., action taken by individuals and enterprises on their own initiative, may reduce the need for explicit adaptation policies.

The technological capacity to adapt to climate change depends partly on the rapidity of climate change and the rate of replacement of equipment and infrastructure. On the whole, the lifetimes of assets in the energy, industry, and transportation sectors are short compared to the timescales for change projected using climate models. Table 11-1, based on Skea (1995), shows that, over the 60–70 years during which CO_2 concentrations in the atmosphere might double, many short-lived assets such as consumer goods, motor vehicles, and space heating/cooling systems will be replaced several times, offering considerable opportunities for adaptation. Even medium-life assets such as industrial plants, oil and gas pipelines, and conventional power stations are likely to be completely replaced over such a timescale, though there will be less opportunity for adaptation.

More difficulties could arise with long-lived assets such as certain residential buildings and infrastructure. Some assets (for example, a dam or a tidal barrage) have a design life of more than a century. Long-lived assets may need to function in a climate for which they were not designed. Infrastructure may be modified during its lifetime, however. For example, roads, port facilities, or coastal protection construction may be rebuilt periodically while retaining the same location and basic function. Rebuilding or upgrading offers substantial opportunities to adapt to changing climate conditions. Even medium-life assets such as power stations may be modified substantially during their lifetime—for example, by changing the fuel inputs, improving efficiency, or adding pollution control equipment.

The technological capacity to adapt to climate change will be realized only if the necessary information is available; enterprises and organizations have the institutional and financial capacity to manage change, and there is an appropriate framework within which to operate. In this respect, autonomous adaptation cannot necessarily be relied upon. Governments

Table 11-1. *Examples of asset lifetimes in the energy, industry, and transportation sectors (based on Skea, 1995).*

Short Life (up to 15 years)	
Conventional light bulb	up to 3 years
Cooking stoves in developing countries	2–3 years
Consumer goods	5–10 years
Motor vehicles	10–15 years
Space heating boilers/air conditioning systems	up to 15 years
Fuel supply contracts	up to 15 years
Medium Life (15–50 years)	
Industrial plant	10–30 years
Renewable energy projects (e.g., solar energy)	10–30 years
Commercial/residential buildings	20–30 years
Conventional power plant	30–50 years
Long Life (>50 years)	
Older residential buildings	50 years plus
Infrastructure (roads, railways, port facilities)	50–100 years or longer
Tidal barrage	120 years

may have a role in terms of disseminating information about climate change, setting policy and regulatory frameworks for individual actions, and acting directly to protect vulnerable infrastructure.

Rapid sea-level rise or changes in climate (Horgan, 1993) would limit the scope for autonomous adaptation, put considerable strain on social and economic systems, and increase the need for explicit adaptation policies.

A good indicator of the capacity for climate adaptation is the importance of the climate signal in relation to other pressures for change in the sector concerned. How do the pressures of climate change compare with those of changing demographics, market conditions, technological innovation, or resource depletion? Over periods of half a century or more, many sectors will change beyond recognition, while others may disappear completely. New products, markets, and technologies will also emerge. An industry coping with other, more significant changes may be able to adapt easily to climate change.

Different regions of the world vary greatly in their capacity to adapt. More vulnerable regions include those with less access to new technology, those that rely heavily on single sources of energy, and those dependent on single crops or on fishing. It has been argued (National Academy of Sciences, 1992) that poverty makes people more vulnerable to change and reduces their flexibility to respond. Both individuals and institutions in developing countries are likely to have less capacity to adapt to a changed climate. If climate change takes place gradually and if the potential impacts of climate change are allowed for in the development process, then the prospects for successful adaptation will be enhanced. Diversifying economic activity could be an important precautionary response that would facilitate successful adaptation to climate change.

Individuals and activities can adapt to climate change by migrating towards other climate zones, even if this involves crossing national frontiers. The migration of economic activity could be regarded as a successful adaptation to climate change. Policymakers at the national level, however, will be concerned about the balance of economic activity and autonomous adaptation actions that affect this activity.

11.1.2. Adaptation and Mitigation

Although the balance between adaptation and mitigation strategies is not the focus of this chapter, mitigation is a key concern in the energy sector. Energy plays a pivotal role in the assessment of climate change since fossil fuel combustion is one of the most important sources of greenhouse gas emissions. The energy sector is therefore likely to be one of the main targets for policies and measures aimed at mitigating climate change. Climate change, however, will also modify patterns of energy demand and industrial activity and, hence, greenhouse gas (GHG) emissions. As a result, the amount of mitigation action required to reach any given target for either emissions or concentrations of GHGs will be altered. At the same time, mitigation actions will themselves modify the impacts of climate on the energy sector—for example, by stimulating switches to more or less climate-sensitive energy resources.

A fully consistent treatment of the industry, energy, and transportation sectors would require an "integrated" approach to the assessment of impacts/adaptation and mitigation. Such approaches are now beginning to be developed (for example, Dowlatabadi and Morgan, 1993; Cohan *et al*., 1994), but few studies take account of feedbacks *within* the energy sector. For the most part this chapter, of necessity, ignores interactions between impacts/adaptation and mitigation actions.

11.2. Characteristics and Sensitivities of the Sectors

Energy, industry, and transportation together cover a wide range of economic activity. Using the international standard industrial classification (ISIC) of all economic activities (United Nations, 1990) as the basis for definition, the sectors cover: manufacturing; mining and quarrying; electricity and gas; construction; transport, storage, and communications; and tourism and recreation.

Among the activities covered in this chapter is agroindustry—the processing of agricultural products into forms that make them suitable for meeting final consumer demands. Food, textiles, and paper are examples of agroindustry. Agriculture, forestry, and fishing, however, are not included. Most of the service sector is not sensitive to climate change, and there are few references in the literature. Notable exceptions are tourism and recreation, which are covered in this chapter, and insurance, which is covered in Chapter 17.

The "energy sector" is spread across a range of ISIC activities and includes: coal, oil, and natural gas production; coke manufacture, refined petroleum products, and nuclear fuel; and electricity generation, electricity and gas transmission, and distribution. Biomass fuels and renewable energy are also covered. Transportation is a major component of the world economy, accounting for 10–20% of gross domestic product (GDP) in most countries. Transportation is growing rapidly; it now accounts for approximately one-fifth of CO_2 emissions from fossil fuel use (Lashof and Tirpak, 1990).

The sensitivity of industry and energy to climate change is widely believed to be low in relation to that of natural ecosystems and agriculture, while adaptability is high (National Academy of Sciences, 1992; Nordhaus, 1993). Different branches of industry, however, vary considerably in their climate sensitivity. Broadly speaking, sectors that are high up the manufacturing chain or are directly dependent on primary resources (agroindustries, renewable energy) display greater sensitivity than do sectors further down the manufacturing chain—for example, engineering. The interactions and interdependence of various activities and systems have been emphasized by some (National Academy of Sciences, 1992; footnote), particularly in relation to adaptive

Table 11-2: *Weight of different sectors in industrial production in 1991 (%), based on UNIDO (1993) and FAO (1993).*

	World	Developed Countries	Developing Countries	E Europe/ former USSR	W Europe	North America	Central and S America	Africa	Asia	Oceania
Energy and Utilities	19.0	15.1	35.5	12.3	15.7	16.7	21.2	N/A	45.0	20.0
- Coal mining	1.5	1.4	0.7	2.9	1.6	1.6	0.2	N/A	1.2	5.0
- Oil and gas production	8.0	3.9	25.2	1.8	4.2	5.9	8.0	N/A	32.6	2.5
- Petroleum/coal products	2.2	1.3	3.5	3.3	1.2	1.4	6.4	N/A	5.5	0.6
- Electricity, gas, and water	7.3	8.5	6.2	4.3	8.7	7.9	6.7	N/A	5.6	11.9
Agro-Industries	20.2	18.0	22.0	26.9	20.5	17.8	31.8	N/A	16.1	18.1
- Food, beverages, and tobacco	11.1	8.9	13.7	17.0	11.1	7.5	21.8	N/A	8.5	11.0
- Textiles	3.7	2.6	4.5	6.6	3.2	2.2	4.2	N/A	4.9	1.8
- Wood products/furniture	3.0	3.4	1.9	2.5	3.4	4.3	2.4	N/A	1.6	3.5
- Pulp and paper	2.5	3.1	1.9	0.8	2.8	3.8	3.5	N/A	1.1	1.8
Other Industry	60.8	66.9	42.5	60.8	63.8	65.5	46.9	N/A	38.9	61.8
- Mining	2.6	2.3	4.2	1.6	0.9	2.2	3.8	N/A	3.3	24.5
- Chemicals	10.3	10.8	11.7	7.5	11.8	10.7	14.6	N/A	7.5	6.2
- Other	47.9	53.8	26.6	51.7	51.1	52.6	28.5	N/A	28.2	31.1
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
% Employed in Agriculture	37.1	5.1	53.6	12.9	6.3	2.2	25.0	61.9	56.5	15.8

Note: N/A = Data not available in original statistical source; figures may not sum exactly due to rounding.

actions. Little work has been carried out that explores these interactions and interdependencies, though some preliminary studies have been carried out (Scheraga *et al*., 1993).

The magnitude of climate impacts is a function of both the severity of the impact and the importance of the affected sector (National Academy of Sciences, 1992). Table 11-2 shows both the contribution of industry to total economic output in different regions of the world and the contribution of different sectors to industrial output (UNIDO, 1993). Broadly speaking, developing countries are less reliant on industry than are developed countries, but climate-sensitive industrial sectors such as energy and food make a relatively greater contribution to economic output in developing countries. The greater importance is reflected even more strongly in terms of employment (UNIDO, 1993). The number of people working in the food industry in developing market economies rose from approximately 10.5 million in 1970 to 17 million in 1990. Between 1977 and 1989, the rate of growth in developing countries was 5.3% per year as opposed to 2.0% per year in industrialized countries (Table 11-3).

The diverse range of activities covered in this chapter is affected by a correspondingly wide range of climate variables (Table 11-4). Temperature changes over daily and seasonal cycles are of key importance, but other relevant variables include precipitation, humidity, ground moisture, insolation, wind speed, storminess, and sea-level rise. Ideally, impacts and adaptation should be reviewed in the context of climate scenarios covering a wide range of variables at the regional level. The uncertainties in present computer simulations of regional climate change, however, are too large to yield a high level of confidence. This, coupled with the sparse use of climate scenario frameworks in most impacts and adaptation work in the industry, energy, and transportation sectors, means that much of this chapter must be restricted to reviewing climate sensitivities. Recent climate scenarios can be used as benchmarks against which to judge reported sensitivities or the results of impact studies based on different climate assumptions. Many existing impact studies are based on assumptions about benchmark CO_2 doubling that have a range of implications for specific climate

Table 11-3: *Economic importance of production and employment in the food industry, in % (UN Statistical Office, 1993).*

Type of Economy	Weight in Industrial Employment (1990)	Annual Growth Rate of Employment (1977–89)	Annual Growth Rate of Production (1977–89)
World	15.5	1.5	2.6
Developed	9.5	-0.4	2.0
Developing	27.1	2.9	5.3

variables, including temperature and precipitation. The following key points highlight differences between current best estimates of climate change and assumptions that have often been made in the climate impacts literature:

- Globally averaged temperatures, which would, for example, influence energy demand, are projected to rise by 0.15–0.25°C per decade. Many impact studies, however, typically assume a 4.5°C increase by the middle of next century and need to be reviewed with more modest temperature increases in mind. Regional temperature changes may be greater or less than the mean.
- Water availability and agroindustry could be affected by precipitation patterns. Precipitation is likely to increase throughout the year at high northern latitudes. In mid-latitudes, winters could be wetter, while summers could be drier. Precipitation during the Asian monsoon season is likely to increase.
- The frequency of extreme weather events has implications for vulnerable infrastructure in the energy, industry, and transportation sectors. There is little agreement on how storminess might change in a warmer world. There is growing evidence, however, that heavy rain events will become more frequent.
- Sea-level rise could affect coastally located infrastructure. The current estimate of average global sea-level rise is 25–70 cm for the year 2100, which is lower than the range presented by IPCC in 1990 and lower than the range assumed in many impact studies. Sea-level rise at the regional level could be as much as twice or as little as half the global average.

11.3. Overview of the Literature

The sensitivity of the industry, energy, and transportation sectors to climate change has received less attention than has the sensitivity of natural ecosystems or agriculture. This reflects the perception that climate sensitivity is relatively low in the industry and energy sectors (National Academy of Sciences, 1992) and the attention focused on the mitigation of climate change through the reduction of GHG emissions (see Chapters 19–22).

11.3.1. Methods

The studies reviewed in this chapter address:

- The sensitivity of specific activities to weather conditions or sea level
- The potential impacts of climate change on a given sector or activity
- The impacts of climate change on a particular country or region
- The broader economic impacts of climate change, typically by integrating the results of work on several sectors into a single macroeconomic model.

While considerable progress has been made in developing protocols for research on climate impacts (Carter *et al*., 1994), most studies do not conform to these standards. The methods used in the studies vary considerably in scope and sophistication. The studies do not yet provide a coherent picture of climate impacts in the industry, energy, or transportation sectors.

The studies vary greatly in their use of climate and socioeconomic scenarios. Sensitivity studies make no use of scenarios but simply identify the effect, or the degree of autonomous adaptation, that a given climate stimulus would induce. Some studies have used an historic “analog” of anticipated climate change (Rosenberg and Crosson, 1991), while others (Smith and Tirpak, 1989) have used the results of scenarios generated by climate models. Many studies that use consistent climate scenarios estimate the effects of climate change on *existing* technology and patterns of economic activity. Such exercises have a heuristic value but cannot be taken as a prediction of the actual impacts of climate change because they do not take adequate account of the impacts of technological and economic changes unrelated to climate and the possibility of autonomous adaptation over timescales of decades.

Only the most sophisticated studies use internally consistent scenarios for socioeconomic change as well as climate scenarios. The industry and energy sectors, however, will change significantly over the next half century. The process of economic development will result in changes in the scale, composition, and location of industrial activity. Technological change, changes in resource availability, and environmental constraints likewise will affect activity patterns. The great uncertainties attached to future patterns of activity are reflected in the range of socioeconomic scenarios that have been developed to describe, for example, future energy demand and supply (IPCC, 1992; World Energy Council, 1993a). The failure to take account of socioeconomic change is one of the greatest weaknesses of the impacts/adaptation literature relating to energy, industry, and transportation.

11.3.2. Biases in the Literature

Research is biased toward specific world regions and sectors. Much of the literature is concerned with impacts in developed

Table 11-4: Summary of climate sensitivities in the industry, energy, and transportation sectors.

	Temperature	Precipitation	Windiness	Frequency of Extreme Events	Water Availability	Sea-Level Rise	Other
Agroindustry and Biomass	Impact on inputs from agriculture	Impact on inputs from agriculture		Damage to crops, trees, industrial infrastructure	Impact on inputs (e.g., irrigation)	Impacts on coastally sited fish processing	Main impacts via inputs from agriculture
Renewables	More evaporation from reservoirs	Hydroelectric potential	Wave potential, reservoir evaporation, wind potential	Many renewable systems vulnerable, especially wind turbines, solar systems	Hydroelectric potential	Design of tidal, wave systems	Cloudiness affects solar potential
Energy Extraction	Impact of reduced ice on offshore Arctic operations			Offshore oil and gas		Offshore oil and gas	
Energy Demand	More space heating, less air conditioning		Space heating				More humidity, more air conditioning
Energy Conversion	Slightly less efficient thermal generation				Cooling water availability	Coastal power stations, refineries	
Energy Transport/ Transmission	Pipelines over permafrost vulnerable; lower capacity of power lines	Icing of power lines		Effects on power lines			
Transportation Infrastructure	Vulnerability if permafrost melts; changed freeze-thaw cycles on roads			Effects on roads, railways, bridges		Effects on coastal infrastructure; migration of coastal activity	Changes in movements of agricultural products; settlement patterns
Transportation Operations	Ice and coastal shipping in high latitudes; road maintenance costs; air conditioning in cars	Impact of snow and ice on road and air transport		Safety and reliability of operations (e.g., airports)	Inland navigation		Effects of fog, snow, rain, and ice on operations and safety

Table 11-4 continued

	Temperature	Precipitation	Windiness	Frequency of Extreme Events	Water Availability	Sea-Level Rise	Other
Tourism and Recreation	Shorter skiing seasons	Skiing season		Impact on attraction of mountainous and coastal regions		Impact on beach resorts and marinas	Many climate variables will affect demand for and location of facilities
Construction	Building design	Changed productivity of construction activity (snow, rain)		Impact on construction activity and building design		Larger markets through coastal zone management	
Manufacturing	More demand for air-conditioning equipment; markets for clothing, beverages				Availability of process water for heavy users; industries heavily dependent on hydropower		
Pollution Control	More ozone formation and control needs		Pollution dispersion		Water quality and discharges		

Note: This table identifies impacts and their degree of significance; the direction of impacts and uncertainties are discussed in the text.
Key: Dark grey boxes indicate a significant impact requiring adaptive response at a strategic level; light grey indicates modest impacts requiring adaptive response; and no shading indicates minor impacts.

countries, especially the United States, which was the first country to produce a comprehensive climate effects report (Smith and Tirpak, 1989). Other developed countries have since published comprehensive reviews (UK Climate Change Impacts Review Group, 1991; Nishioka *et al*., 1993), and some work has been carried out in developing countries (Nguyen *et al*., 1993). Recent impact studies covering transportation refer only to developed countries such as Canada, New Zealand, and the United States (Nishioka *et al*., 1992). Such studies generally analyze only the direct impacts of climate on infrastructure and operations. Climate-induced changes in flows of freight and passengers that would affect infrastructure demands have been acknowledged but not quantified.

There are also biases in terms of the topics covered in the literature. The potential impact of climate change on demand for electric power and the consequent impact on investment in new power capacity accounts for a significant proportion of the energy-related literature (e.g., IPCC, 1990b, 1993). The ready availability of information relating electricity demand to weather conditions enables work of some sophistication to be carried out. The topic, however, may not be as important as the volume of literature would suggest.

11.3.3. Framework for the Review

This review classifies economic activity in three ways:

- Economic activity with markets sensitive to climate change
- Economic activity that is directly sensitive to climate
- Economic activity that is dependent on climate-sensitive resources.

Given the wide range of activity covered in this chapter, impacts and adaptation have been covered jointly under each topic.

This framework, which is simpler than that used in the first IPCC Assessment Report (IPCC, 1990b), highlights interactions among different branches of industry and linkages among industry, energy, transportation, and other sectors, such as agriculture and human settlements. These interactions may transmit climate sensitivities through the economic system and are critical to an understanding of the broader impacts of climate change. Table 11-5 splits economic activity into four broad sectors—energy, agroindustry, transport, and other sectors—which are subdivided further into narrower bands of activity. It identifies those classes of climate sensitivity to which each sector is subject and gives a broad indication of the degree of sensitivity. The energy sector and agro-based industries show, in a qualitative sense, the greatest sensitivity. Since energy is an input to most other industrial activity, the impacts of climate change as reflected in energy costs will cascade through the industrial sector. Water (Chapter 14) is another important vector for transmitting climate sensitivity through an economy.

Markets for consumption goods, intermediate goods, capital goods, and transportation services all may be affected by climate change. The task of reinforcing coastal defenses in response to climate change, for example, will fall on the construction industry. Changing flows of freight and passengers will affect investment in new transportation infrastructure. Climate change will influence patterns of energy demand and, consequently, the need for investment in power plant and other supply facilities. Consumer demand for clothing and beverages and, in some parts of the world, air conditioning equipment, will also be altered by climate change.

Economic activity directly sensitive to climate is found in the construction, electricity, oil, gas, transportation, and water sectors. For oil and gas, offshore production is more sensitive than onshore production. In addition, some industrial activity is located in zones that are sensitive to climate change. Oil refining and some types of power generation, for example, tend to be located in coastal zones in order to facilitate the transport of raw materials and products. Transportation is vulnerable through the effects of sea-level rise on coastal infrastructure and the more direct effect of weather on operations. Constructions in the permafrost regions are especially vulnerable to climate change.

Climate-sensitive resources on which industry is dependent include agricultural, forestry, or marine products; water; energy; and various raw materials. Among the sectors and activities that are affected are food, beverages, and tobacco; textiles, leather, and clothing; timber products; pulp and paper; renewable energy; and sectors such as aluminum that are heavily dependent on hydroelectricity.

Table 11-5: *Sectors sensitive to climate.*

	ISIC No.	Markets	Production	Resources
Energy				
Oil and gas production	11	–	**	–
Oil refining	23	–	*	–
Electricity and gas	40	**	*	**
Biomass	N/A	–	–	***
Hydropower, wind	40	–	–	***
Other renewables	40	–	–	*
Agroindustries				
Food, beverages, tobacco	15,16	*	–	***
Textiles	17	*	–	**
Wood and products	20	–	–	*
Pulp and paper	21	–	–	*
Rubber	25	–	–	*
Pharmaceuticals	part of 24	–	–	*
Transport				
Transport, storage, and communications	60–63	*	*	–
Other Industry				
Water industry	41	***	***	***
Construction	45	**	*	–
Tourism and recreation	55 + others	***	–	**

*** = Significant impact requiring adaptive response at a strategic level.
** = Modest impact requiring adaptive response.
* = Minor impact.
N/A = Activity not easily classified within ISIC.

11.4. Economic Activity with Climate-Sensitive Markets

11.4.1. Energy Demand

The two uses of energy most sensitive to climate change are space heating and air conditioning in residential and commercial buildings and agricultural applications such as irrigation pumping and crop drying. Supply companies will adapt by changing the amount of new investment required to meet peak demand on electricity and gas networks and the composition of investment that would most cost-effectively meet changed temporal patterns of demand. Many studies that assess the impact of climate change on building energy demand have been conducted. The majority focus specifically on electricity markets. A smaller number of studies address energy demand in the agricultural sector and impacts on energy supply investments. The impact of climate change on energy demand will be perceptible but modest in relation to the impact of factors such as changes in technology and patterns of economic activity.

This chapter is primarily concerned with the consequences of climate change for the energy supply sector. Chapter 12 focuses on the impacts of changed energy demand in buildings and their occupants. Climate change also could lead to the increased use of air conditioning in motor vehicles; the resulting reduction in fuel efficiency is discussed in Section 11.5.2.

11.4.1.1. Energy Demand for Space Heating and Air Conditioning

11.4.1.1.1. Space heating and air conditioning markets

The mix of energy sources used for space heating varies widely from one region of the world to another but may include electricity, fossil fuels (coal, oil, or gas), or wood. Patterns of energy use in residential and commercial buildings are discussed in Chapter 22 on mitigation options in human settlements. Among the key points are (Hall *et al.*, 1993; Schipper and Meyers, 1992; World Energy Council, 1993a):

- The significant use of biomass fuels in developing countries
- The heavy use of coal in China, Poland, and other countries
- The increase in natural gas use in Europe and North America over the last 2 decades
- An increasing market share for electricity in new homes.

In the commercial sector, air conditioning accounts for a greater proportion of final energy demand than in the residential sector, due partly to internal heat gains from lighting, office equipment, and occupants. The use of air conditioning is still quite low in temperate regions of the world, though its use is growing because the use of electronic equipment is adding to internal heat gains and sealed buildings help to isolate occupants from a noisy or polluted environment (Herring *et al.*, 1988). The use of air conditioning is growing rapidly in a number of developing countries (Schipper and Meyers, 1992). As described in Chapter 22, energy demand in buildings is growing rapidly in developing countries and in countries with economies in transition but is virtually level in the industrialized world.

11.4.1.1.2. Climate sensitivity

The factors determining the use of energy for space heating and air conditioning are discussed in Chapter 12 in relation to human settlements. Energy suppliers, particularly in the electricity and gas sectors, are highly conscious of the link between energy demand and climate because peak capacity needs are determined for extreme weather conditions. In the UK, for example, where natural gas is the dominant heating fuel, annual send-out can vary by as much as ±10% because of variations in annual average temperature. In the UK, the climate-related variability of gas demand since the mid-1980s has been much larger than it was over the period 1950–85 (British Gas plc, 1992).

11.4.1.1.3. The impacts of climate on energy demand

Many national studies assessing the impact of climate change on energy demand have been carried out. The studies cover the United States as a whole (Linder *et al.*, 1989; Niemeyer *et al.*, 1991; Rosenthal, Gruenspecht, and Moran, 1995); Finland (Aittoniemi, 1991); the UK (Parry and Read, 1988; UK Climate Change Impacts Review Group, 1991; Skea, 1992); Japan (Nishinomiya and Kato, 1990; Kurosaka, 1991; Matsui *et al.*, 1993; Nishioka *et al.*, 1993); and New Zealand (Mundy, 1990). Unpublished work on the former Soviet Union also has been carried out. Within the United States, there also have been a number of regional studies covering: Missouri, Iowa, Nebraska, and Kansas—"MINK" (Darmstadter, 1991); the Pacific Northwest (Wade *et al.*, 1989; Scott *et al.*, 1993); the Southeast and New York State (Linder *et al.*, 1989); and the Tennessee Valley (Miller and Brock, 1988). Some work has addressed specific categories of energy demand such as air conditioning (Milbank, 1989; Scott *et al.*, 1994). Chapter 12 also considers some of these studies.

Table 11-6 summarizes the results of regional and national studies that have sought to quantify the relationship between climate change and energy demand. Table 11-6 illustrates the great diversity in climate scenarios, time-frames, the focus in terms of fuels or specific energy end-uses, and the methodologies used. Climate sensitivities have been deduced either from established statistical relationships between weather and energy demand or from projected climate-induced changes in physical parameters such as degree days. The merits of the two approaches are discussed in Chapter 12. Table 11-6 demonstrates the strong emphasis that has been placed on the study of impacts on electricity demand, probably because this issue is "directly analyzable" (National Academy of Sciences, 1992). Although the results of the various studies are very location-dependent, several broad themes emerge:

- **Fossil Fuel Demand**—Climate change will cause the use of fossil fuels for space heating to decline. For example, a temperature increase of 1.3–2.9°C in the UK could reduce the demand for natural gas by 7–20% in 2050 compared with demand without the effects of climate change (UK Climate Change Impacts Review Group, 1991). In the MINK (Missouri, Iowa, Nebraska, Kansas) region of the United States it has been suggested that fossil fuel demand for space heating would decrease by 7–16% as a result of a temperature increase of 0.8°C (Darmstadter, 1991).
- **Electricity Demand**—Whether electricity demand is likely to rise or fall as a result of climate change depends on the relative importance of space heating or air conditioning (Linder *et al*., 1989). In areas with a high summer load associated with cooling, climate change will result in increased electricity demand. Conversely, where there is a high winter load associated with space heating, demand is likely to fall. In some temperate zones, where air conditioning is growing in importance, it is not clear whether in the long-term the increase in demand for cooling will exceed the reduction in demand for heating (UK Climate Change Impacts Review Group, 1991).
- **Total Energy Demand**—According to a study referring to representative residential buildings conducted by the Japan Architecture Society (1992), temperature rise will lead to a reduction in energy consumption in Sapporo (43°N), whereas in Tokyo (36°N) the reduction of energy for heating in winter is balanced by an increase due to cooling in summer. At Naha (26°N), the overall energy load will be increased by 50 MJ/m^2 due to a 1°C temperature rise. Rosenthal, Gruenspecht, and Moran (1995) concluded that a 1°C global warming would reduce total U.S. energy use associated with space heating and air conditioning by 1 petajoule (PJ), 11% of demand, in the year 2010. Costs would be reduced by $5.5 billion (1991$). A 2.5°C global warming would reduce total costs by $12.2 billion (1993$). This estimate accounts for the latitudinal and seasonal variations in warming but not for daily variations.
- **Peak Demand**—In the UK, peak demand for heating fuels will decline less than total annual demand, leading to a reduced demand load factor. This would be due partly to a shorter heating season (UK Climate Change Impacts Review Group, 1991). The seasonal occurrence of the peak demand for electricity is an important factor. If peak demand occurs in winter, maximum demand is likely to fall, whereas if there is a summer peak, maximum demand will rise. The precise effects are highly dependent on the climate zone (Linder and Inglis, 1989). Climate change may cause some areas to switch from a winter peaking to a summer peaking regime.

11.4.1.1.4. Impacts on investment in electricity supply

Fewer studies have estimated the possible impact of climate change on investment requirements in electricity supply. An exception is the "infrastructure" component (Linder and Inglis, 1989) of the U.S. national climate effects study (Smith and

Table 11-6: *Summary of results of studies relating climate change to energy demand (based on Ball and Breed, 1992).*

Study	Country/ Region	Temperature Change (°C)	Date	Method	Coverage	Change in Annual Demand	Change in Peak Demand
Aittoniemi, 1991	Finland	1.2–4.6			electricity	7–23% down	
Darmstadter, 1991	U.S. MINK	0.81	2030	degree days	agriculture cooling heating	3% up <2% up 7–16% down	
Matsui, 1993	Japan		2050		electricity	5% up	10% up
Rosenthal, Gruenspecht, and Moran, 1995	USA	1	2010	degree days	space heating and cooling	11% down	
Smith and Tirpak, 1989	USA	3.7	2055	weather analog	electricity	4–6% up	13–20% up
UK Climate Change Impacts Review Group, 1991	UK	2.2	2050	degree days	all energy electricity	5–10% down 1–3% down	

Tirpak, 1989). The principal *quantitative* conclusions arising from that study, under one scenario based on large regional temperature rises in the range 3.4–5.0°C by 2055, were that:

- By 2010, peak demand would increase by 29 gigawatts (GW), or 4% of the baseline level for that year. For 2055, peak demand could be increased by 181 GW, or 13% of the baseline level.
- By 2010, additional investment in new capacity attributable to climate change would be 36 GW, or 13% of the new capacity requirements in the baseline scenario. By 2055, the extra capacity needed could be 185 GW, or 16% of new capacity requirements.
- Cumulative generation costs could be 5% higher by 2010 and 7% higher by 2050.

Among the more qualitative conclusions regarding adaptation to climate change were that:

- There could be a need for relatively more peaking, as opposed to baseload, capacity.
- The generation fuel mix would be altered.
- Different regional impacts could lead to more transfers of power from one area to another.
- Construction requirements and greater levels of fuel use may cause further environmental damage.

11.4.1.2. Energy Demand in Agriculture

Changes in energy demand in agriculture will largely be driven by changes in the level of food production on existing land, especially in developing countries. Changes in energy inputs to fertilizers would be an important indirect impact. Climate change, however, would have some direct impacts on energy needs. The MINK study (Darmstadter, 1991) included some approximate estimates of the impacts of a 0.6–0.9°C temperature rise on energy needs for irrigation pumping and crop drying. Energy demand for pumping would rise by around 25%, while demand for crop drying would decline by around 10%. Irrigation pumping demand is likely to be more sensitive to changes in temperature than to changes in precipitation (Wolock *et al*., 1992). Taking into account the proportion of agricultural energy demand associated with pumping and drying, Darmstadter concluded that energy demand in agriculture in the MINK region would rise by less than 3% as a result of climate change. This conclusion appears not to have been based on any specific assumptions about climate-induced changes in cropping patterns.

11.4.2. Space Heating/Air Conditioning Equipment

Markets for air conditioning equipment are growing independently of climate change. A broader discussion will be found in Kempton (1992) and Andrews (1989). A small number of studies concerning the weather dependency of demand for air conditioners has been conducted. According to new work on patterns of electricity consumption carried out by the Tokyo Electric Company (1994), for example, electricity consumption in the company's supply area rose exponentially during 1990 when air temperatures exceeded 17°C, with most of the increase due to air conditioning. In Japan, sales of air conditioners tend to rise by 40,000 units per day of maximum temperature of over 30°C (Sakai, 1988).

11.4.3. Construction

The construction industry, which is very weather sensitive, embraces architecture, building, and civil engineering. The direct impact of climate change on construction *activity* is addressed in Section 11.5. This section focuses on the impact of climate change on various types of construction and on the level of demand for construction work.

The construction industry carries out work both above and below ground in a wide range of terrains, some sheltered, others exposed. A variety of specific types of construction, including port facilities, are needed in coastal zones. The construction industry also plays an important role in the development of river and other hydrological works. These include dams, water supply systems, and works that safeguard against risks such as flood and urban drainage failure. Other works are required to secure water quality. The industry is also responsible for the civil engineering component, above and below ground, for land-based transportation systems such as roads, railways, oil/gas pipelines, and electric power lines, as well as airports. All of these works are climate sensitive.

11.4.3.1. Climate Sensitivities

The problem of assessing the impacts of likely climate change on construction falls into two distinct parts (UK Climate Change Impacts Review Group, 1991):

- The assessment of the likely impacts of climate change on existing constructions. Modifications needed to counter any unacceptably adverse effects of climate change must be identified. The appropriate timing for modifications must also be decided.
- The assessment of how current design practices might require modification. This assessment should also address design changes that could reduce future emissions of GHGs and other pollutants.

The key climatic risks in relation to constructions are high wind, snow load, driving rain, thermal expansion, excessive rates of weathering, thawing of permafrost, and sea-level rise. In general, risks are created by extreme values and events (for example, very high winds) rather than average conditions. Therefore, the use of climate models to predict changes in the magnitude and frequency of extreme events is a prerequisite for assessment work in this area. There are great uncertainties attached to the future frequency of extreme events at the regional level. Other risks are associated with the increased vulnerability of timber and timber products to insect and fungus attack, the interaction of short wave radiation with cloudiness, and the impact of ambient temperatures on indoor climate (Page, 1990).

11.4.3.2. Adaptation to Sea-Level Rise

The construction industry will be called on to implement adaptation options associated with sea-level rise. The degree to which coastal infrastructure is at risk is described in Chapters 9 and 12. Existing protective constructions, such as breakwaters and sea walls, will also be affected by sea-level rise. A number of examples serve to illustrate the likely consequences.

Titus *et al*. (1991) estimate that about 2,600 km^2 of low-lying land in the United States may need to be protected from sea-level rise. The cost would be \$5–13 billion for a 50 cm rise—approximately the current best estimate for the year 2100—and \$11–33 billion for a 100 cm rise. Dikes would not be used on barrier islands because of their narrowness and aesthetic considerations. As a result, 420 km^2 of land on Atlantic Coast islands would need to be gradually raised. The cost of elevating buildings would be \$15 billion under the 50 cm sea-level rise scenario and \$30 billion under the 100 cm scenario. Gradually elevating roads and other infrastructure may be cheaper than building dikes. This has very different implications for the construction industry.

Hata *et al*. (1993) have assessed the impact of sea-level rise on Japanese fishing ports and adjacent coastlines. Quantitative analyses were performed for three different types of fishing ports assuming sea-level rises of 65 cm and 110 cm. It would be necessary to increase the height of the design wave and, consequently, the weight of breakwater structures. Breakwater weight would need to be increased by more than a factor of two assuming a very high sea-level rise scenario of 110 cm. An increase in the structural buoyancy of loading wharves and sea walls would result in a loss of stability. In addition, loading activities and vessel mooring functions would be impaired. In some cases, the surrounding communities themselves would be subject to severe flooding. Kitajima *et al*. (1993) have estimated a cost of \$92 billion for protecting Japanese ports, harbors, and adjacent coastal areas against sea-level rise.

An even greater amount of construction activity might be required in Africa, where industry tends to be concentrated in capital cities, many of which are seaports (Tebicke, 1989).

11.4.3.3. Building Design and Climate Change

The technology of building design and construction will continue to evolve over the next half century, permitting adaptation to changed climate conditions. In temperate zones, the use of air conditioning systems has grown (UK Climate Change Impacts Review Group, 1991). In principle, climate change would stimulate the wider introduction of air conditioning systems. In practice, however, this will be influenced by other changes in building design. The use of suitable design techniques could obviate the need for air conditioning systems in many buildings.

A survey by the Japan Architecture Society (1992) identified the following impacts of climate change on urban planning and architecture:

- The effect of wind, solar radiation, and air pollution in urban areas
- The effect of temperature rise and wind upon architecture, indoor climate, and human adaptation
- Effects on the thermal capacity of concrete, asphalt, and other building materials
- Effect on the use of water in buildings.

The greatest negative impacts on constructions are likely to arise from the interaction between sea-level rise and inland water hydrology. The impacts will be in vulnerable areas. The stability of foundations built on shrinkable soils would be affected by increased winter rainfall combined with drier summer soil conditions. Southeastern England, for example, has many properties at risk (Boden and Driscoll, 1987). Building design codes, currently based on historical climate records, may need to be changed in order to anticipate risks assessed in climate impact studies.

11.4.4. Demand for Transportation Infrastructure and Services

Transportation activity and associated energy consumption are growing very rapidly. Recent trends and future projections are discussed in Chapter 21 on mitigation options in the transportation sector. The essential points are:

- Air and highway transport are the fastest growing modes.
- The fastest rates of growth will take place in developing countries.
- Transport-related CO_2 emissions could rise by between 40 and 100% by 2025.

With the exception of electrified rail and pipelines, transportation relies entirely on fossil energy, principally petroleum. Alternative fuels remain a very minor energy source for transportation, although the ethanol-from-biomass experiment in Brazil is notable (Sperling, 1987). Fossil fuels account for a significant share of tons moved in freight transport. In the United States, coal and petroleum constitute 30% of rail carloads, while petroleum, coal, and coke comprise 60% of waterborne ton-miles. Agricultural and food products are second to energy in terms of freight ton-miles. Changes in the location and nature of agricultural activities could have a large impact on the freight transport system.

Climate-induced changes in the distribution of population and economic activity and the consequent effects on the performance of transportation infrastructure and infrastructure needs are of great potential importance. Transportation requirements are closely linked to patterns of human settlement and have been addressed in this context in several infrastructure-based assessments (e.g., Walker *et al*., 1989). Changes in the nature and location of agricultural production, in the rates of population growth in different regions, in the volumes and types of fossil fuels used, and in tourism and recreational travel can have profound effects on the performance of existing transportation facilities and on requirements to construct new ones. Although it is widely acknowledged that climate change could produce significant redistributions of population and economic activities, particularly agriculture, detailed geographic predictions of these phenomena are lacking (Johnson, 1991; Jansen *et al*., 1991). Such regional predictions are a prerequisite for quantitative assessment of the impacts of regional redistribution on transportation.

Existing assessments of transportation impacts have recognized the potential significance of changes in geographical patterns of economic activity on the transportation network. Black (1990) notes that even gradual, long-term global warming could cause a major disruption of the movement of goods and people in North America. Irwin and Johnson (1988) suggest that there would probably be a northward spreading of agricultural, forestry, and mining activities, resulting in increased population and intensified settlement patterns in Canada's mid-north and even in Arctic areas. Marine, road, rail, and air links would have to be expanded accordingly. While this would entail substantial extra capital and operating costs, it would also be an economic opportunity.

While increasing temperatures may open up regions to increased development in northern climates, sea-level rise may also force massive migrations from settlements on river deltas and other low-lying areas. Jansen, Kuik, and Spiegel (1991) point out that a possible 26% land loss in Bangladesh would displace 27% of the population and that a 21% land loss in Egypt would displace 19% of the population. The implications of such a population movement for transportation infrastructure requirements have not been addressed.

To date, no quantitative assessments of the impacts of climate on demand for transportation in areas such as tourism and recreation have been made, partly because the necessary regional economic scenarios do not exist (see Section 11.5.9). The current state-of-the-art in intercity passenger and freight transportation modeling is adequate for quantifying major changes in flows and predicting the magnitude of changes in transport networks that would be required to accommodate them (Friesz *et al*., 1983; Bertuglia *et al*., 1987). The interactions that would have to be modelled are represented in Figure 11-1. Climate change affects the geography of specific climate-sensitive sectors such as agriculture and tourism, but it also affects population distribution and regional economic growth more generally. Actions taken to mitigate climate change affect other activities, notably the extraction, processing, and distribution of fossil fuels. Changes in the location of these activities

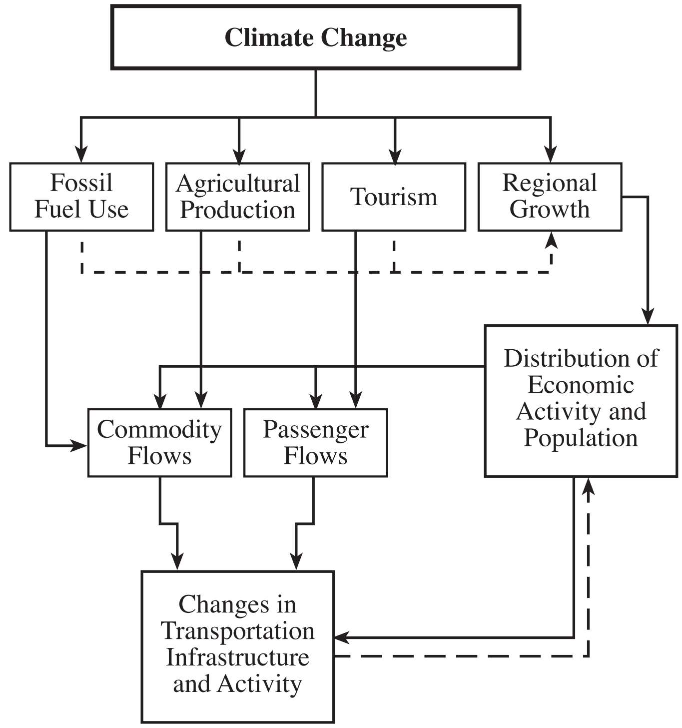

Figure 11-1: Indirect effects of climate change on transportation.

affect the demand for flows of passengers and freight on a regional and global level. These demands then influence the development of transportation infrastructure and transportation movements. In addition, there are feedback effects by which the transportation infrastructure and activity influence patterns of regional growth. The anticipation of climate change would be appropriate in planning investments of a long-lasting infrastructural nature.

11.4.5. Other Market Impacts

The first IPCC assessment report (IPCC, 1990b, Chapter 5, Section 5.2.1.1) reported that climate change could be expected to influence patterns of demand for food, beverages, and clothing. The report suggested that:

- There could be an increased demand for cold drinks such as carbonated beverages, fruit juices, lemonade, and iced tea, and a reduced demand for hot beverages such as hot coffee or tea.
- There could be an increased demand for cotton clothing and certain synthetics and a potential reduction in demand for wools.

At the time, no studies that investigated these possible patterns of change could be cited. This remains the case. While some change in demand for beverages and textile products may be likely as a result of global warming, changes will take place over the long term, and the impacts may be small compared with those induced over a shorter timescale by product innovations and changes in consumer preference.

11.5. Economic Activity Sensitive to Climate

A wide range of economic activity displays some degree of direct sensitivity to climate change. On the whole, the direct impacts of climate change will be minor compared to impacts on resources or markets. The direct effects on activity located on coasts or in permafrost regions could be greater, however. Affected sectors include construction, transportation, energy, and tourism.

11.5.1. Construction

Rain, snow, high winds, and frost all hinder construction. Increased rainfall in winter, which may occur in mid-latitudes, would reduce productivity directly through impacts on working conditions and indirectly through impacts on ground conditions. A warmer winter climate could reduce the negative impacts of frost on construction activity. In areas such as Siberia, however, warming could cause permafrost shrinkage and lead to structural damage. If wind speeds were to increase, there would be a need to pay greater attention to wind protection during construction. Existing work on the variability of the impacts of present climate on the construction process could provide a basis for examining future climate impacts on site production (UK Building Research Establishment, 1990). A study in Japan reported that warm winters and springs have a favorable impact on the ceramic and quarrying industries, while the following have a negative impact: extended periods of rain in early summer, heavy snow, cool and rainy summers, and typhoons (Tokyo District Meteorological Observatory, 1986). Typhoons and other heavy rain, which may increase, can reduce the production of cement tiles and concrete blocks because of their impact on drying processes (Fukuoka District Meteorological Observatory, 1987).

11.5.2. Transportation Operations and Infrastructure

Climate change will have some direct effects on transportation infrastructure and the operation of transportation systems. These may be divided into three categories: the effects of climate on operations, the effects of sea-level rise on coastal facilities, and the effects of climate on infrastructure. These subjects have been included in existing impact studies in which transportation has been treated as one component of human settlements (e.g., Daniels *et al*., 1992; Walker *et al*., 1989).

11.5.2.1. Transportation Operations

Global warming will have both negative and positive impacts on the operation and maintenance costs of transportation systems. Studies in temperate and northern climates have generally indicated that higher temperatures will result in lower maintenance costs, especially with fewer freeze-thaw cycles and less snow (Parry and Read, 1988). Black (1990) points out, however, that increased pavement buckling due to longer periods of intense heat also is a possibility. Engineering standards for facility design and maintenance represent a sound, if not completely precise, means of quantifying the relationship between climate and factors such as damage to roads and bridges from freeze-thaw cycles, snow removal costs, salt application, and de-icing. Data from cities with similar climates and engineering handbook standards have been used to quantify the relationship (e.g., Walker *et al*., 1989).

Inland and coastal water transport is particularly sensitive to droughts, floods, changes in water levels, and icing over of ports and waterways. The MINK study (Frederick, 1991) suggested that lower flows in the Missouri River could shorten the navigation season in the United States Midwest from eight months to five months in six of every ten years. Navigation benefits on the upper Missouri, however, are only $14 million/year, and the MINK study was based on a dry, 1930s-analogue climate rather than a forward-looking climate scenario.

In colder regions, the most significant direct impact of warming is likely to be on inland and coastal water transportation. A longer season for Arctic shipping is likely, with a greater number of frost-free days for northern ports and inland waterways such as the St. Lawrence Seaway (Irwin and Johnson, 1988). Inland waterways, however, may suffer loss of depth for greater periods of seasonal drought, reducing their usefulness for commercial shipping (Black, 1990). A survey of the potential impacts on Canadian shipping suggested net benefits to Arctic and ocean shipping due to deeper drafts in ports and longer navigational seasons, but mixed results for lake and river shipping due to the opposing effects of a longer shipping season but lower drafts (Irwin and Johnson, 1988). In Siberia, many rivers are used as solid roads during winter. Warmer winters would require a shift to water transport or the construction of more all-weather roads. Other climate impacts could arise from changes in snowfall or melting of the permafrost (IBI Group, 1990).

Transportation operations are sensitive to the weather. Fog, rain, snow, and ice slow down transport movements and increase risks of accidents. In addition, maintenance costs and the durability of infrastructure are somewhat dependent on weather events. Changes in the frequency and intensity of catastrophic weather events of short duration (for example, hurricanes, floods, wind shear, and surface movements associated with high rainfall) may have significant impacts on the safety and reliability of transportation. Little evaluation of such factors has been attempted.

Transportation operations are also affected by temperature. Fuel economy is somewhat temperature sensitive, primarily because of the time it takes a vehicle to warm up (Murrell, 1980). The impact on overall fuel economy of a few degrees' increase in average temperature, however, is likely to be a fraction of a percent. Vehicle emissions are also affected by temperature, especially evaporative emissions of hydrocarbons (U.S. EPA, 1989). This is potentially significant because formation of tropospheric ozone, for which hydrocarbons are a precursor, also tends to increase with temperature (see Section 11.5.7).

Increased use of air conditioning in vehicles would have a greater impact on overall fuel economy than would the direct effect of temperature change. U.S. automobiles consume 47 liters of fuel to operate air conditioners for every 10,000 km driven (Titus, 1992). Titus suggests that a CO_2 doubling would increase expenditure on fuel by $1-3 billion annually because of more air conditioning, though many of the specific assumptions used to reach this conclusion are not transparent. CO_2 doubling is assumed to be associated with a 3°C temperature rise. A warmer climate would also increase energy demand associated with refrigerated transport and cold storage (Steiner, 1990).

Interruptions to transportation operations can have significant impacts on industry. During the 1988 drought in the United States, industries that relied on bulk transportation of raw materials and finished products by barge on the Mississippi River found that low water kept more than 800 barges tied up for several months. In 1993, by contrast, floods in the upper Mississippi valley disrupted the barge transportation system. To the extent that industry is moving toward just-in-time production systems, it will become more vulnerable to interruptions for these and other reasons. This issue is also discussed in Chapter 17 in relation to financial services.

11.5.2.2. Sea-Level Rise and Coastal Infrastructure

Transportation infrastructure could be lost to inundation in coastal areas when sea levels rise and shorelines recede, although port infrastructure may be rebuilt sufficiently often to avoid such threats. Many airports are located at low levels. The impacts of sea-level rise have been rigorously examined in a few studies. In a detailed assessment of impacts at six sites on the eastern and Gulf coasts of the United States, Daniels *et al*. (1992) found that impacts varied greatly from city to city. For example, under a low sea-level rise scenario, 40% of the transportation, communications, and utilities infrastructure of Galveston, Texas, would be below mean sea level by 2050, and half by 2100. Under the moderate and high sea-level rise scenarios, approximately half would be below sea level by 2050 and all by 2100 (Daniels *et al*., 1992, Table 4.7). A similar study of the Daytona Beach, Florida, area concluded that only about 10% of the transportation infrastructure was subject to inundation (Daniels *et al*., 1992, Table 4.19). The impacts of sea-level rise on transportation infrastructure in low-lying countries such as Bangladesh and Egypt would be massive (U.S. Department of Energy, 1990).

Walker *et al*. (1989) found that considerable damage to roads in the Miami, Florida, area would be caused by a higher water table. If the sea level and water table were to rise by roughly one meter, the subgrade and/or base of many city streets would be subject to a certain amount of saturation given the annual fluctuation in the water table and its proximity to the surface. Structural failure would be caused if a heavy load were to pass over the surface. The cost of raising vulnerable streets in Miami was put at $575/meter for 410 km of road, or $237 million. Walker *et al*. (1989) also found that bridges and causeways that were not inundated would be damaged considerably if not reconstructed. Climate change should be anticipated when constructing or rebuilding transportation infrastructure.

11.5.2.3. Other Infrastructure

Inundation is not the only threat of sea-level rise to transportation infrastructure. Extreme rainfall could have widespread impacts on roads, railways, and other transportation links. As long as rainfall does not become more intense, impacts on urban roads and railways in temperate, tropical, and subtropical zones are likely to be modest. Exceptions could occur in coastal areas where highways and bridges may have to be redesigned for the higher wind pressures of tropical cyclones (Deering, 1994). In mountainous regions, increased intensity of rainfall could increase the risk of mudslides.

11.5.3. Energy Transportation and Transmission

Electricity transmission lines are susceptible to extreme weather events. If the frequency of extreme weather events were to increase, customers would have to accept a less reliable electricity service or pay for the costs of strengthening lines. Storms in Northern Europe in October 1987 led to an average loss of 250 minutes supply to customers of the UK's Central Electricity Generating Board (Electricity Council, 1988). As discussed in Chapter 17, the cost of interruptions to power supply in many service sectors is rising due to the increased use of advanced information and communication technologies. The capacity of electricity transmission lines also drops at higher temperatures. For example, the capacity of the typical line used in the UK falls from 2,720 megavolt-amps (MVA) in winter to 2,190 MVA in summer (Eunson, 1988). Higher temperatures could have minor implications for utilities experiencing a summer peak. Possible thawing of permafrost in Arctic regions may require changes in the design of oil pipelines in order to avoid slumping, breaks, and leaks (Brown, 1989).

11.5.4. Offshore Oil and Gas

Offshore production of oil and gas could be affected to a minor extent by sea-level rise. Royal Dutch Shell has increased the height of North Sea gas platforms above the water level by 1–2 meters to take account of projected sea level rise (National Academy of Sciences, 1992). This will, however, add less than 1% to the total cost of a platform.

Increased wave activity and increased frequency of extreme weather events might have a more significant effect on offshore operations, but little research has been conducted on this topic. Offshore oil and gas production conducted at high latitudes may be assisted by a longer ice-free season (Lonergan, 1989). A recent Canadian study of the Arctic petroleum industry (McGillivray *et al*., 1993) concluded that *global* temperatures rising by 1–4°C over a period of 50 years and Arctic temperatures rising by two to three times as much would:

- Increase the open water (ice-free) season in the Canadian sector of the Beaufort Sea from 60 to 150 days
- Reduce ice thickness
- Increase the maximum extent of open water in summer from the current 150–200 to 500–800 km offshore
- Increase wave heights (e.g., the proportion of waves in excess of 6 m would rise from 16 to 39%).

As a consequence of reduced ice thickness and more open water, the offshore petroleum industry could experience reduced operating costs. The most critical factor could be ice movement during winter. Increased wave activity, however, would push up design requirements for both offshore structures and associated coastal facilities. In adapting to climate change, the industry would prefer to take a cautious view of these conclusions, discounting the benefits and preparing for increased wave activity (McGillivray *et al*., 1993).

11.5.5. Thermal Power Generation

The efficiency of electricity generated through both steam and gas cycles would be affected negatively, though in a minor way, by global warming (Ball and Breed, 1992).

Most current thermal electricity generation relies heavily on the availability of cooling water (Smith and Tirpak, 1989; Solley *et al*., 1988). There is a general trend away from once-through cooling, in which water is returned to rivers, toward evaporative cooling. In the United States, there also is a movement away from river-based power plants toward coastal siting (Smith and Tirpak, 1989). New technologies, such as combined-cycle gas turbines, are reducing the dependence of fossil fuel-fired power generation systems on the availability of cooling water (UK Climate Change Impacts Review Group, 1991). For these reasons, the impact of changes in water availability should be relatively minor.

Power plant output may be restricted because of reduced water availability or thermal pollution of rivers with a reduced flow of water. Events such as these have occurred during droughts in several parts of the world including France and the United States (*Energy Economist*, 1988). Under more extreme temperature conditions, some nuclear plants might shut down to comply with safety regulations (Miller *et al*., 1992).

11.5.6. Water Availability for Industry

Changing patterns of water activity, particularly at the regional level, are highly uncertain. Industrial manufacturing depends upon water and is affected by its availability in several ways:

- Water is used as an ingredient or processing solvent for pulp and paper, food processing, textiles, and petrochemical refining (see Section 11.6.1).
- Some sectors, such as aluminum and, increasingly, the steel industry, are dependent on electrical energy and in particular on cheap hydroelectricity. Other industries are dependent upon water for process cooling or, indirectly, for cooling water in thermal electric power stations.
- Many industries are dependent upon cheap river and lake barge transportation of bulk raw materials and for shipping finished materials.
- The location of many manufacturers along rivers makes them vulnerable to damage from flooding.

Reductions in rainfall, which are possible during the summer in mid-latitudes, could adversely affect manufacturers in the first three categories by raising the cost of water, energy, and transportation as inputs into their products. Low water levels and higher temperatures could lead to less dissolved oxygen and greater problems with biochemical oxygen demand for industries that utilize water as an ingredient or solvent. This could raise the cost of process water. Efforts to reduce the use of process water through recycling could substantially reduce vulnerability to water shortages.

The global aluminum industry is exceptionally energy intensive and, in 1990, utilized an estimated 280 terawatt-hours (TWh) of electricity (Young, 1992) to convert alumina into 16.3 million metric tons of primary aluminum metal (Plunkert and Sehnke, 1993). Production of aluminum metal is distributed among 41 countries, many of which lack bauxite ore but possess abundant energy resources. The United States is unusual in that only 12.4% of its energy for aluminum production comes from hydroelectricity (Aluminum Association, 1991), whereas most of the other major producers—such as Brazil, Canada, and Ghana—rely almost exclusively on hydroelectricity (Plunkert and Sehnke, 1993). In the six years since 1988, Russian exports have expanded six-fold and now account for 10% of world production (Imse, 1994). Hydroelectricity forms the basis for the development programs and the industrial base of many developing countries. Brazil, for example, now ranks fourth in the world in terms of hydroelectricity production after Canada, the United States, and the former Soviet republics. Developing countries would be particularly hard hit by a reduction in hydroelectricity capacity. Any reduced availability of hydroelectricity could have significant adverse consequences for the industry.

Other industries that might be affected by a decline in regional electricity production are electric arc furnace-based steelmaking, electroplating, and uranium fuel enrichment. Regions suffering a decline in water availability from altered precipitation patterns would see rising water prices. Adaptation would require the development of additional water supply resources, the adoption of less water-intensive processing methods or, alternatively, relocation.

11.5.7. Pollution Control and Climate Change

Some features of climate change could lead to changes in ambient levels of pollution in both air and water. The two possible impacts that have been given brief consideration in the literature are accelerated rates of ozone formation caused by higher temperatures and possible reductions in water quality caused by lower levels of river flow.

Estimates of the impact of temperature change on ozone formation vary. Gery *et al*. (1987) estimate that a temperature rise of 2–5°C would cause ozone concentrations in several major U.S. cities to rise by 1.69 ± 0.37% for every 1°C of warming. Morris *et al*. (1989) estimate that maximum ozone concentrations over a large part of the United States would rise by 1.45 ± 0.50% for every 1°C of warming. One form of adaptation would be to reduce emissions of ozone precursors. Smith and Tirpak (1989) estimate that, in order to maintain air quality, emissions of volatile organic compounds (VOCs) arising from auto exhausts, organic solvents, and gasoline storage would need to be reduced by up to 2% for every 1% increase in ozone concentration. U.S. VOC emissions for the year 2005 have been estimated at approximately 14 million tons (Pechan and Associates, 1990), suggesting that a 2°C temperature rise would add some $1.4–4.2 billion to annual VOC control costs, assuming abatement costs of $1,900–5,500/ton. As discussed in Chapter 12, there are also severe urban air pollution problems in Eastern Europe and in many cities in developing countries. The losses associated with increased air pollution would therefore be geographically widespread (Cline, 1992).

Maintaining water quality under conditions of reduced river flow would similarly require reductions in the discharge of pollutants. Titus (1992) estimated the impacts of an arbitrary CO_2 doubling on water flows in each of the U.S. states and calculated the cost of maintaining water quality. Across the United States, annual water pollution control costs were estimated to rise by $15–52 billion. Titus concluded that maintaining water quality would have a higher cost than problems directly associated with reductions in water quantity. In other parts of the world, however, river flows could increase and water quality would not be reduced.

11.5.8. Coastally Sited Industry

Many industries are located preferentially in coastal zones that are discussed in detail in Chapter 9. In the energy sector, many petroleum refineries and power stations are located in coastal zones because of ready access to supplies of crude oil and fuel or because of the availability of cooling water. In the UK, all oil refineries and more than half of the thermal power stations are located on coastal sites (UK Climate Change Impacts Review Group, 1991). Sea-level rise could result in additional expenditures at existing sites (Smith and Tirpak, 1989; Nishinomiya and Kato, 1990; UK Climate Change Impacts Review Group, 1991). There is a considerable amount of infrastructural investment (transmission lines, transport routes) associated with existing energy facilities, and any major migration of activity is unlikely.

11.5.9. Tourism and Recreation

Tourism and outdoor recreation is one of the most important and rapidly growing service industries throughout the world. In many countries, tourism is a major source of employment. Countries with economies that are highly dependent upon tourism may face great challenges because the resources upon which tourism rests are regionally, nationally, and globally climate-dependent.

Tourism and recreation are sensitive to climate change because part of the industry is closely associated with nature (National Academy of Sciences, 1992). Some parts of the tourism and recreation industry will necessarily migrate as a result of climate change. The Academy panel concluded that the overall effect for a country as large as the United States would probably be negligible, though specific regions could experience adverse or favorable effects. The question of whether the dislocations or relocations caused by climate change will produce costs over and above those that would have been incurred otherwise is important, but difficult to answer.

Two of the most obvious tourism and recreation facilities exhibiting climate sensitivity are skiing and beach resorts. In general, global warming might be expected to reduce the length of the skiing season in many areas and to affect the viability of some ski facilities. On the other hand, the summer recreation season in many areas may be extended. In some coastal areas, the benefits resulting from a longer season may be offset, however, by the loss of economically important beaches and coastal recreational resources, particularly on low-lying and vulnerable tropical islands.

Several studies have projected shorter skiing seasons as a result of climate change. Aoki (1989) found that skiing activity in Japan was highly sensitive to snowfall. In a study of the implications of an effective CO_2 doubling on tourism and recreation in Ontario, Canada, Wall (1988) projected that the downhill ski season in the South Georgian Bay Region could be eliminated, with an annual revenue loss of $36.55 million (Canadian dollars). This outcome assumed a temperature rise of 3.5–5.7°C and a 9% increase in annual precipitation levels. Some of these losses would be offset by an extended summer recreational season. Lamothe and Periard (1988) examined the implications of a 4–5°C temperature rise throughout the downhill skiing season in Quebec. They projected a 50–70% decrease in the number of ski days in Southern Quebec, while ski resorts equipped with snow-making devices would probably experience a 40–50% reduction in the number of ski days.

Because many recreational activities and related facilities are associated with coasts and beaches, sea-level rise may be of special concern to the recreational and tourist industries. Boathouses, residential plots and houses, public buildings, and structures are increasingly under threat due to sea-level rise. The low-gradient recreational beaches characteristic of much of the Atlantic and Gulf coasts of the United States are very vulnerable to erosion. Titus *et al*. (1991) estimate that the cost of sand required to protect major United States recreational beaches from a 50 cm sea-level rise would be $14–21 billion. In addition, elevating infrastructure would cost another $15 billion on the Atlantic coast alone. Several U.S. states have prohibited seawalls on the ocean coast. Texas, Maine, and South Carolina allow public beaches to migrate inland with the shoreline. Property owners must take the risks of an eroding shoreline into account. Sea-level rise could affect fixed waterfront facilities such as marinas and piers. There could be increased erosion of beaches backed by sea walls, leading to a lowering of the beach level and subsequent undermining of the walls. Recreational habitats such as sand dunes, shingle banks, marshlands, soft banks, soft earth cliffs, and coral reefs would also be affected.

A small number of national studies of the potential impacts of climate change on tourism have been conducted. Higher temperatures are likely to stimulate an overall increase in tourism in the UK, with the greatest impact being on holiday activity and some forms of outdoor recreation (UK Climate Change Impacts Review Group, 1991). An increase in sea temperature would increase the pressures of tourism on UK beaches, while coastal erosion may reduce beach area (Baker and Olsson, 1992). A study by the Tokyo District Meteorological Observatory (1986) found that warm springs, falls, and winters, the absence of a rainy season, and very hot, dry summers have a favorable impact on tourism. On the other hand, typhoons, cool and rainy summers, extended periods of rain in the early summer, heavy snow, and cool springs were found to create unfavorable conditions.

11.6. Economic Activity Dependent on Climate-Sensitive Resources

Agroindustry, biomass production, and renewable energy sources depend heavily on climate-sensitive resources and therefore are potentially vulnerable to climate change.

11.6.1. Agroindustry

The impacts of climate change on the primary products of agriculture, forestry, and fishing are carried over to the food and drink sector, industries dependent on forestry products such as pulp and paper, and other sectors, notably textiles. The food and beverage industry is almost completely dependent on agricultural products, with the exception of mineral waters and some soft drinks. The textile and clothing industry is slightly less dependent due to synthetic fibers. In this chapter, these sectors are described collectively as *agroindustry*.

Many assessments of the impacts of climate change on specific crops and on agriculture as a whole have been carried out (Chapter 13). The few conceptual or empirical studies of agroindustry suggest that the sector is indeed vulnerable to climate change. Most of the assessments refer to developed rather than developing countries. Agroindustry, however, is relatively more important in economic terms in developing countries. Moreover, even in the case of industrialized countries, analyses focus on only a few countries, notably the United States. The narrow range of studies carried out is unfortunate because it is virtually impossible to define generic thresholds for the impact of climate variables on agroindustries, even when the same product is derived from the same raw material.

11.6.1.1. Economic Impacts on the Food Industry

11.6.1.1.1. Agriculture-agroindustry linkages

The literature on the impacts of climate change on agroindustry has advanced little since the IPCC Supplement (IPCC, 1993). The U.S. MINK study addresses the linkages between agriculture and agroindustry at a regional level (Rosenberg and Crosson, 1991). Scheraga *et al*. (1993) have examined the consequences of higher agricultural prices resulting from CO_2 doubling using a general equilibrium model. Kane *et al*. (1992) have assessed the economic effects of CO_2 doubling on agricultural commodities at a global level. Some national studies exploring the linkages between primary agricultural products and subsequent processing also have been conducted (UK Climate Change Impacts Review Group, 1991; Antal and Starosolzky, 1990; Comisión de Cambio Climático, 1991). Most of these studies are concerned only with the impact of changes in the mean values of climatic variables on agriculture and agroindustry. Extreme weather events, however, can also carry climate impacts from the primary agriculture sector to agroindustry. The resource base of agroindustry is particularly vulnerable to droughts and tropical cyclones. Such cyclones can also severely damage industrial infrastructures, mainly small and medium-sized factories.

The MINK project (Rosenberg, 1993; Bowes and Crosson, 1993) quantified the links between agricultural production and processing industries. A climate similar to that of the 1930s was superimposed on current and projected patterns of economic activity. The work indicated strong linkages between the regional meat packing industry and feedgrain production and between soybean cultivation and oil production. More than 80% of the outlays by soybean oil mills are accounted for by purchases of oil-bearing crops.

The overall effect of the expected decline in feedgrain production on the regional economy depends on the extent to which the decline affects domestic or export markets. The decline could be as much as 6–10% if drops in production were to affect only domestic markets through the impact on the local meat-packing industry. The authors believe, however, that the economic impact would be closer to 0.6–1.0% because of adaptation on the part of farmers, the possible benefits of higher CO_2 concentrations, and the likelihood that reduced grain output would primarily affect export markets. The higher production costs in MINK under the 1930s climate would weaken the region's competitive position in world grain markets. Over the long term, some animal production might shift to other grain-producing regions less affected by climate change. This could induce a decline in meatpacking in MINK, because these activities tend to be near animal production (Bowes and Crosson, 1993).

Scheraga *et al*. (1993) used a general equilibrium framework to explore the impact of a fairly extreme change in climate on agricultural production costs and the prices of goods and services that use agricultural commodities in the United States. The effects of selected climate impacts on the gross national product (GNP), consumption, investment, and the sectoral composition of output were assessed. A projected decline in crop yields was assumed to raise agricultural prices by more than 20% by 2050. This has an indirect effect on prices in other sectors, as shown in Figure 11-2. The largest price increases occur in agroindustry, notably the food sector, causing food and tobacco output to decline by 10%. Scheraga *et al*. (1993) calculated that the economic burden of climate change would fall disproportionately on lower-income households, which spend a large share of their income on food. This consequence of climate change, applicable to U.S. conditions, could be even more pronounced in developing countries.

Kane *et al*. (1992) examined the impacts of a doubling of atmospheric CO_2 concentrations on world agriculture and the indirect impacts on agroindustry. The study assumed increased precipitation and warming in the high northern latitudes coupled with drying in continental interiors. This work emphasized the importance of trade effects as a result of changes in the relative importance of the agricultural and industrial sectors and the direction and magnitude of the world price effects. Under two scenarios, prices of the main commodities used in food-related agroindustry were projected to rise by between 1 and 37%. The study projected only modest impacts on national economic welfare, which depends on changes in the yield of domestic agriculture, changes in world commodity prices, and the relative strength of the country as a net food importer or exporter. The benefits to producers will be larger than the losses to consumers if the country, like the United States, is a large exporter. This conclusion emphasizes the vulnerability to climate change of agriculture and agroindustries in the majority of developing countries. Rosenzweig and Parry (1994) also note that many cereal-producing countries in the tropical and subtropical zones appear more vulnerable to the potential impact of global warming than are countries in temperate zones.

The link between agriculture and agroindustry has been explored qualitatively in a number of country studies. In the UK, a rise in temperature coupled with increases in rainfall would accelerate the rate of deterioration of food and would change crop production patterns. Reduced rainfall, possible in summer, would reduce production, increasing raw material costs and requiring the import of more raw materials for the food industry (UK Climate Change Impacts Review Group, 1991). In Hungary, an increase in droughts would lead to a decrease in the yield of pastures, which would reduce the economic viability of cattle stocks and the associated meat processing industry (Antal and Starosolzky, 1990).

11.6.1.1.2. Impacts on specific food products

From the literature it is possible to draw more specific examples of the possible indirect impacts of climate change for grain, sugar cane, and fish products.

Grains constitute the world's staple food. In terms of agroindustries they are used in the production of bread, flour, meals, and pasta and form an essential input to the meat processing and dairy industries through animal production. Rosenzweig *et al*. (1993) conclude that climate change will lead to a decrease in cereal production, mainly in developing countries. Warming, coupled with drier climates in the interior of continents in the northern middle latitudes, predicted by most climate models, could have negative impacts on crops and livestock in the United States, Western Europe, and southern Canada, which are the most important grain-producing areas of the world (Kane *et al*., 1992). Increased precipitation and warming in the high northern latitudes, however, could enhance agricultural production potential.

The northward shift of the North American corn and wheat belt, as a consequence of drier conditions in the Midwest, could bring benefits to Canada, increasing its grain production and export capacity (Smit, 1989). Any shift in the corn belt also would entail large social and environmental costs. Some communities, industries, and the associated physical infrastructure could cease to be viable and might need to be relocated (U.S. Department of State, 1992). Affected agroindustries might include the production of ethanol and sweeteners, both of which are currently expanding.

World sugar production is 100 million tons per year, 60% of which is derived from sugar cane and 40% from sugar beet (UN Statistical Office, 1993). Sugar cane is also used to manufacture distilled alcoholic beverages and ethanol for motor fuel. According to Leemans and Solomon (1993), the distribution of sugar cane in a warming world could be quite similar to that at present, with the possibility of some expansion of the cultivated area. Yields per unit area could be increased by 3.4% and global production by 16.2%. This is based on the assumption that agroindustry associated with sugar cane will be developed intensively for energy production. The expansion of sugar cane for use as an energy source would be aided by the successful development of biomass gasification technology coupled to gas turbines (Larson, 1993). The greater use of sugar cane could form part of climate change mitigation strategies because this would contribute to reductions in greenhouse gas emissions (Acosta and Suarez, 1992; Macedo, 1991).

Sugar cane is produced in a large area of the world extending from 37°N to 31°S. Within that belt there are huge climatic differences (Blume, 1985). Consequently, local conditions must be addressed in assessing climate change impacts. This underlines the impossibility of defining generic thresholds for the impact of climate variables on agroindustries. A study of the productivity of Cuban sugar mills has shown that temperature and, to a greater extent, rainfall patterns are the principal climatic factors

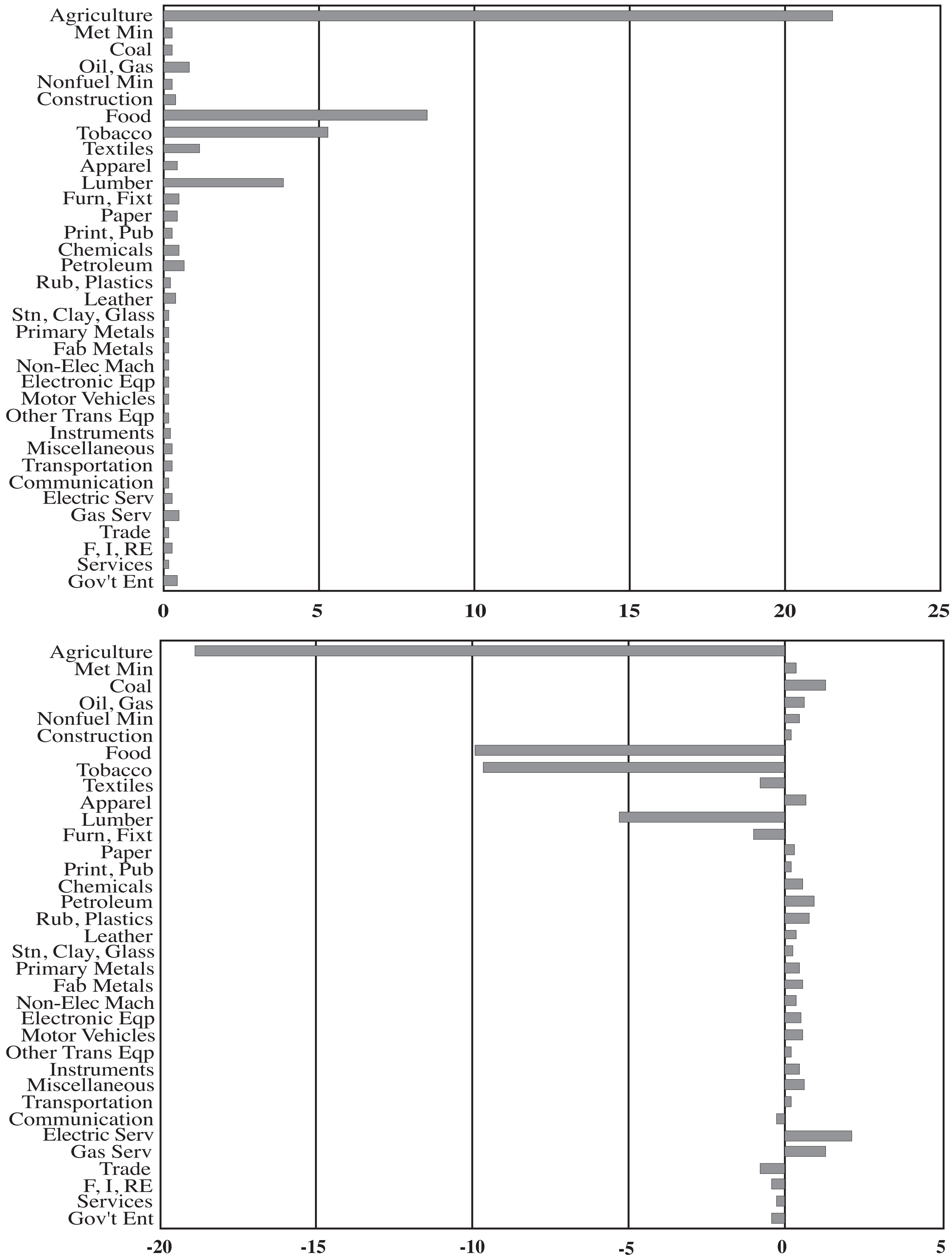

Figure 11-2: Percent change in sector supply prices (top) and domestic output (bottom) for the year 2050, as a consequence of projected decline in crop yields (Scheraga *et al*., 1993).

influencing sugar production (Comisión de Cambio Climático, 1991). The sugar industry could also be threatened by an increase in the frequency and intensity of hurricanes. Central America, the Caribbean, and Fiji have recently been struck by a number of severe hurricanes that damaged sugar production.

Citrus fruits are the basis for the large-scale production of beverages and other agroindustrial products. The impact of extreme climate events has contributed to important changes in the map of world citrus production. Frosts have a dramatic impact on the production levels of citrus (Buzzandi, 1979). Between 1957 and 1985, the citrus industry in Florida was subject to periodic freezes resulting in widespread production losses (Bulger, 1985; Miller and Glantz, 1988). The freezes in 1980–85 reduced seasonal orange production by about 50%. Those impacts helped to consolidate the expansion of agroindustry based on citrus fruits in Brazil, which was able to increase its exports during a period of rapid industrialization (Castello and Carvalho Filho, 1992).

Climate change would affect fish processing through both the availability of resources and impacts on storage systems. Fish processing comprises the freezing, salting, and drying of fish and the manufacture of fish jelly products, canned products, oil and fat, feed, and fertilizer. Seaweed is also economically significant in some parts of the world. The largest pressures on fish processing in some parts of the world will arise from overfishing and reduction in stocks. Fish jelly products and frozen fish, however, are sensitive to temperature change. Since fish processing industries are usually located along the sea coast, facilities are vulnerable to sea-level rise. For example, Stokoe (1988) notes that fish processing facilities in Canada's Atlantic provinces have a capital value of $1 billion (Canadian dollars), and most are situated at or near the water's edge. They could be vulnerable to inundation or damage as a result of sea-level rise. Reductions in precipitation could reduce potable water needed for fish processing. This is currently a problem due to climate variability, and significant permanent changes could cause additional difficulty.

Higher temperatures and sea-level rise could reduce catches of cod, tuna, and green hata in the Gulf of Tonkin, although the profitability of the shrimp industry could rise due to increased production (Nguyen *et al*., 1993).

11.6.1.1.3. Key issues for the food industry

The conclusions of the small number of country studies and more general studies can be drawn together:

- Impacts on the food industry depend mainly on changes in the availability and price of agricultural products. Therefore, adaptation measures in agriculture are the key to diminishing any negative impacts on agroindustry.
- Climate change could have a severe impact on regions or countries dependent on single crops. Diversification of economic activity could be an important precautionary response.
- The impacts of climate change for agroindustry will be more pronounced in developing countries than in developed countries because many are located in more vulnerable zones and because their capacity for adaptation is lower.
- The burden of climate change may affect lower-income households disproportionately.
- Climate change could cause a loss of competitiveness in agroindustry in specific countries or regions, especially in developing countries. This could affect the viability of communities, industries, and associated physical infrastructure, resulting in relocation and/or large social and economic costs for the affected regions. On the other hand, some countries or regions might benefit.

11.6.1.2. Industry Dependent on Forestry

Many industrial sectors are dependent on forest products, including wood and timber, pulp and paper, rubber, and pharmaceuticals. Other forest products include nuts and oils. A recent analysis of the potential for products other than timber from a region of the Amazon concluded that their annual market value could be double that of timber itself (Peters *et al*., 1989). Many forest products originate in developing countries where the commodities play a large role in the local and national economies. The sensitivity of forestry to climate is discussed in Chapter 15.

Forests provide major components for the construction of buildings in most parts of the world. Substantial amounts of furniture and a lesser proportion of other home utensils are manufactured from wood. In Europe, Russia, and North America, indigenous forests support major domestic timber industries. In many developing countries in the tropics, wood is a common property resource used as the predominant building material and for manufacturing agricultural/domestic tools and implements. Significant losses of forests in the North due to climate change would have major economic consequences. In the South, such losses could affect livelihoods, especially in rural areas.

The pulp and paper industry now relies most heavily worldwide on a combination of virgin forests and tree plantations as its source of fiber. Forests with rotation times of 30–50 years or longer are particularly vulnerable to climate change. In North America, the original Canadian boreal forest is still a principal source of newsprint, although short-rotation pine plantations harvested every 20 years in the southeastern United States contribute an increasing share. Europe relies upon boreal plantations in Scandinavia and coniferous plantations in Germany. The vast taiga of Siberia has supplied pulp and fiber for Eastern Europe in the past, but those traditional market relationships have been disrupted. Recent work has raised concern that the very slow regeneration time of the Siberian taiga could lead to major long-term deforestation of the region. Models suggest that changes in albedo accompanying climate change could produce significant *cooling* in the region that would further diminish regrowth.

In industrialized countries, forests are likely to remain the primary source of raw materials for paper manufacture. In developing countries, the per capita demand for paper is still growing rapidly. Some developing countries may need to utilize other sources of raw materials. In 1989, 161 paper mills worldwide utilized bagasse (dry residue) from sugar cane (Silverio *et al.*, 1991). Mexico produced 8.5% of its paper from bagasse in that year (Atchison, 1989). China and other Asian countries use rice stalks in traditional paper making, and there is also the potential for utilizing cellulose fiber from other annual plant sources for pulp. Annual crops such as these are far less vulnerable to climate change.

The main source of natural rubber is the rubber tree, grown principally in Southeast Asia at latitudes below 10°N. More than six million hectares of land were used to produce 4.8 million tons of natural rubber in 1987 (UNIDO, 1993). Extreme temperatures can kill the tree, and relative humidity below 60–65% decreases the production of rubber resin (Tran *et al.*, 1979; Pham, 1973; Le, 1988). Excessive humidity or rainfall would encourage disease and pests (Tran *et al.*, 1979; Tayhieu Station, 1969; Chee, 1977). An increasing frequency of typhoons and tornadoes could cause significant damage to rubber plantations in countries such as Indonesia, the Philippines, Thailand, and Vietnam (Enquête Kommission, 1991; IPCC, 1990a; Tran, 1990). In Malaysia, the main rubber-producing country, yields could decline by 15% under a CO_2 doubling scenario associated with a regional temperature rise of 1–2°C and a 10% increase in rainfall (Asian Development Bank, 1994). Yield loss could rise to 25–40% due to the effects of temperature on the viscosity of resin when the tree is tapped. In Indonesia, the Philippines, coastal South Asia, and Indochina, warming for a CO_2 doubling could be in the range 0.5–3.0°C (CSIRO, 1992a). Adaptation to climate change could involve preparing for new developments outside the 10°N latitude zones. Plantations could be protected from high winds and colder winds by planting dense buffer trees to act as windbreaks. Increased irrigation could be used in Africa and parts of Asia, which might become drier. All of these measures could push up the cost of natural rubber and encourage substitution of synthetic material. This would damage the economies of rubber-growing countries.

Climate change could reduce biodiversity in forested regions, which in turn could reduce the availability of pharmacologically active natural products derived from plants, bacteria, and animals (Wilson, 1992). A quarter of the prescription pharmaceutical drugs dispensed in the United States between 1959 and 1973 had plant-derived active ingredients (Farnsworth and Socjarto, 1985). Plants provide 15–20% of pharmaceuticals in Japan and provided 35–40% in West Germany before unification (Principe, 1989a). The total market value of plant-derived pharmaceutical drugs was an estimated $43 billion in the Organisation for Economic Cooperation and Development (OECD) countries in 1985 (Principe, 1989b).

While it is difficult to make precise links between climate change and species loss, attempts to identify climate-altered conditions that might lead to extinction have been made (Gates, 1993; Wyman, 1991; Rose and Hurst, 1992; Emanuel *et al.*, 1984). Each of these studies predicts major relocation of species and ecosystems. Many species, especially trees, are unlikely to be able to migrate successfully if climate change occurs rapidly.

Surveys suggest that the tropics remain the most potentially productive source of future drugs, especially the Amazon (Peters *et al.*, 1989) and Costa Rica (Tangley, 1990). Most of the focus to date has been on the commercial potential of drugs for markets in industrialized countries, but populations in tropical countries might be disadvantaged if local species upon which they have come to depend for medication were to disappear because of climate change.

11.6.1.3. Textiles

Four fibers form the basis of the textile industry: cotton, wool, cellulosic fibers (rayon), and synthetics. Other fibers—for example, silk and linen—make up a small fraction of the total. Climate has little effect on synthetic fibers, but industries that rely upon natural fibers will be affected in a variety of ways by climate change.

Warming is likely to increase the risk of disease vectors and insect pests for cotton, sheep, and the forest sources of cellulose (Smith and Tirpak, 1989). Altered water availability is most serious for the growing of cotton, which is heavily dependent on irrigation in Central Asia, Egypt, and other parts of the world. Altered precipitation patterns could diminish the usefulness of large reservoirs and water distribution systems. Sheep are most often raised on marginal, drier lands such as in Australia, which accounts for nearly 70% of the world trade in wool for apparel (*Economist*, 1992). The boundaries of suitable grazing regions are likely to shift under any significant alteration of climate. Since many tree species are suitable for producing cellulosic fibers, they are much less vulnerable to altered precipitation patterns.

All fibers require massive amounts of water for processing and dyeing. One ton of wool requires an estimated 200,000 liters of water from shearing to the finished fabric (Watson, 1991). Cellulosic fibers require substantial amounts of water in the pulpmaking process, and cotton and wool require substantial amounts for cleaning. Synthetic fibers require relatively little water after the petroleum refining stage. Approximately 70% of water use is associated with the dyeing of finished cloth (Watson, 1991). Recycling could reduce the degree of dependence on water.

If precipitation patterns were to shift significantly, the production of finished cloth and industrial fibers might shift away from regions that were becoming drier. There might also be a shift toward synthetic and cellulosic fibers, which are less vulnerable. Apparel, carpet, tire cord, and other industries dependent on textile fiber are relocating in response to changing labor markets. This suggests that textile industries located close to supplies of raw materials might respond rapidly to climate-induced changes in availability. While global production might not be greatly altered, the loss of industries might have significant local effects.

11.6.2. Biomass

Biomass is estimated to account for 12–15% of global primary energy consumption (World Energy Council, 1993b; Hall *et al*., 1993). After oil, coal, and natural gas, biomass is the world's most important source of energy. Trees are the most important source (64%) of biomass fuels in both urban and rural areas. The remainder consists of animal dung and crop residues used in the countryside. A total of 88.5% of wood biomass is used as firewood and the rest as charcoal (Smith *et al.,* 1993). Biomass is the most important source of energy in developing countries, where it accounts for 38% of consumption (Hall *et al.,* 1993). In some of the least industrialized countries, where there is limited access to electricity grids, 90% of energy needs is met by biomass. Financial constraints may also force people to use biomass in cities (see Chapters 12 and 22). Biomass in the domestic sector is used primarily for cooking, although it is also used for space heating in regions with cold winters—for example, Nepal and northern China. Biofuels are transported to cities by draft animals and lorries, sometimes over long distances. In the Sahelian countries of Africa, biofuel trade is a well-organized sector with impressive turnovers (Sow, 1990). Biogas generated by anaerobic fermentation is used mainly in the Asian countryside. According to Dutt and Ravindranath (1993), more than four million family house generators have been installed in China and one million in India. The numbers are growing rapidly.

In industrialized countries, biomass accounts on average for 2.8% of primary energy consumption (Hall *et al.,* 1993). The share is, however, 13% in Scandinavia and 5% in France and the United States (Corté, 1994; and FAO, 1994). In industrialized countries, most biomass is used for household heating in rural areas and small towns. For example, this accounts for 81.5% of biomass consumption in France (Barbier *et al.,* 1994). Usually, fuelwood is burned in stoves in the industrialized countries, though woodchips are becoming more popular for district heating in Austria and Scandinavia. Large amounts of biomass are collected directly by users, bypassing the market system (Riedacker and Robin, 1987).

In both developing and industrialized countries, agroindustries use large amounts of biomass wastes for energy generation. Cogeneration is important in the sugar cane industry in the United States, Cuba, and Mauritius (Turnbull, 1993). These industries do not generally need to buy extra biomass to meet their energy demand. In developing countries, biomass, mainly fuelwood, is also used for drying tea and tobacco, for processing food, for cremation, and for public baths. There is an increasing demand for biofuels in small industries in countries such as India and Brazil (La Rovere, 1994). Large amounts of charcoal based on eucalyptus are used in Brazilian steel mills (Sampaio, 1994).

Biomass is also used for transportation fuels. In Brazil, liquid biofuels accounted for 18% of transportation fuel in 1987 (Goldemberg *et al*., 1993). There are about fifty facilities manufacturing ethanol fuel from grain, mainly maize, in the United States. In 1987, this accounted for 8% of the U.S. gasoline market (Wyman *et al.,* 1993). Zimbabwe also has started to produce ethanol from sugar cane.

11.6.2.1. Impacts of Climate Change on Domestic Biomass

Fuelwood supply depends very much on forest area and the quantity and pattern of rainfall. As deforestation proceeds around cities in developing countries, mainly to provide more cropland, fuelwood has to be transported greater distances (see also Chapters 12 and 22). Forest yields are likely to be reduced with decreasing rainfall. Thus, in dry and densely populated areas, fuelwood may become more scarce due to a combination of population growth and climate change. The projected deficit of demand over supply could be most critical in tropical Africa (see Chapters 1 and 15).

The growth of annual and perennial plants is likely to increase with CO_2 enrichment and higher temperatures. Forested areas may expand northward, increasing resources in industrialized countries. Biomass resources are expected to increase in Italy (Bindi *et al.,* 1994), for instance, but this depends on the precise nature of any climate change as well as on the crop and the crop system used (see Chapters 1 and 13). Except in regions with reduced rainfall, future biomass supply in industrialized countries is likely to exceed the present demand. As discussed in Chapter 19, more intense biomass production to substitute for fossil fuels may become an important mitigation option in countries with good rainfall regimes. This would also be the case in Latin America and tropical Africa.

Biomass can be converted to methane gas through anaerobic conversion in digestors. The rate of methane production increases at high temperatures and may be interrupted in winter, for example, in North China (Rajabapiah *et al.,* 1993). Global warming may therefore lengthen periods during which high yields can be obtained and extend the areas in which biogas can be produced without heating the digestor, for example, in households.

11.6.2.2. Impacts of Climate Change on Industrial Biomass

The impact of climate change on the availability of agricultural wastes for electricity production and cogeneration will be similar to the impact of climate change on the supply of food and agricultural raw materials. Industries and biofuel production dependent on brought-in supplies of annual biomass crops are more vulnerable. Raw material is more costly to transport than is food.

Large fluctuations in the yield of biomass energy systems could have greater impacts on system reliability and costs than might be estimated by extrapolating experience gained from food crops (Hillman and Petrich, 1994). In 1993, ethanol production from sugar cane in Zimbabwe stopped completely due to an extreme drought. The impact of extreme events on industries dependent on wood biomass are likely to be less dramatic.

11.6.2.3. Adaptation to Gradual Change

In general, decreasing rainfall will lower biomass production, particularly in the low latitude countries. Changes in rainfall intensity and evapo-transpiration will also be relevant. In some tropical and semi-arid countries, adaptation may become necessary before climate change becomes perceptible because of population growth and deforestation around cities. Adaptation could take the form of either switching to new fuels or more efficient production and conversion of biomass.

As forests become more scarce, increasing amounts of fuelwood may be derived from trees planted on private land. Countries that face fuelwood or charcoal shortages and cannot afford or do not want to switch to imported fossil fuels could develop small-scale projects to test the feasibility of new biomass conversion and production techniques. Adaptation will be especially necessary in areas with low land availability or low growth potential—for example, arid and semi-arid regions. Biofuel supply from trees, shrubs, grass, or crop residues can be increased or maintained by the following means:

- Better management of natural resources by giving local populations a stake in sustainably grown forests (Bertrand, 1993)
- Planting more trees on agricultural land and establishing better prices for biofuels derived from these plantations to provide rural incomes and incentives to grow more biomass
- Carrying out research to identify higher yielding species, preferably trees and shrubs, that are easy to propagate and are better adapted to extreme conditions like droughts and acidic or saline soils (Riedacker *et al.,* 1994)
- Increasing the productivity of agricultural land.

More details about these measures are provided in Chapters 1, 13, 15, and 25. There are many technologies that can contribute to the improved conversion of biomass (Antal and Richard, 1991; Mezerette and Girard, 1990).

11.6.2.4. Adaptation to Extreme Events

Energy systems based on a mixture of biofuels and fossil fuels are likely to be less vulnerable to climate change than systems based on a single biofuel. Options that reduce vulnerability include injecting gas derived from biomass into natural gas networks, gasohol (a mixture of gasoline and ethanol), or methanol, which can be derived from biomass, natural gas, or coal. Electricity generation plants that can use either perennial or annual crops also will be less vulnerable (Larson, 1993).

11.6.3. Renewable Energy

As discussed in Chapter 19, the accelerated development of renewable energy systems—for example, solar energy and wind—could help to mitigate emissions of greenhouse gases. Mitigation strategies are likely to have the largest impact on the development of renewable energy, but climate change could modify the potential to some degree:

- By increasing or decreasing the flow of the renewable energy resource being used (e.g., hydroelectric potential)
- By affecting the technology used to collect or convert the resource into a useful form, generally in ways that increase system costs or reduce performance (e.g., if high winds damage photovoltaic installations)
- By affecting willingness to develop renewable energy systems, if climate change places stress on ecosystems or reduces the value of the resource.

Renewable energy systems tend to be developed first at locations that have the best resources and that can be developed to yield useful energy at the lowest cost. Climate change might, at favorable locations, increase the availability of some renewable resources. Others, such as solar radiation, are affected only by changes in cloudiness. Developers of renewable energy systems tend to match equipment carefully to the characteristics of the site, taking account of factors such as the flow of the renewable resource. This both increases the amount of the resource used and reduces the delivered cost of energy. A change in climate can reduce the quality of the match between installed technology and a site's resources, thereby increasing cost, wasting resources, or reducing performance. Hillsman and Petrich (1994) provide a comprehensive review of the possible impacts of climate change on renewable energy systems. Any negative effects of climate change on the operation and cost of renewable energy systems need to be set against positive benefits arising from their role in GHG mitigation strategies.

11.6.3.1. Impacts on Resources

11.6.3.1.1. Hydroelectricity

Hydroelectricity is currently the most exploited renewable energy resource around the world. The principal pathways through which climate could affect hydroelectric resources are through a change in precipitation or the conditions (temperature, insolation, wind, humidity) that affect evaporation from reservoirs. Precipitation can change in quantity, seasonality, and form (for example, snowfall versus rainfall). The percentage of a basin's supply lost to evaporation from reservoirs or lakes depends not only on how much of the basin they cover but also on temperature, wind, and humidity, as well as vegetation cover and the location of a basin's reservoirs in relation to precipitation sources (Cohen, 1987a, 1987b). In an arid region, a change in temperature alone might have less effect on evaporation than it would in a more humid one. All else being equal, reductions in precipitation should also tend to reduce humidity and therefore increase evaporation. An increase in transpiration from vegetation can also reduce the net supply of water to a basin.

An analysis of hydroelectric generating potential in the James Bay region of Quebec under two climate scenarios estimated that an increase in precipitation would outweigh an increase in evaporation, and that generation could increase 6.7–20% (Singh, 1987). Possible responses to decreased production include reliance on other generating sources or the use of demand-side management (*Energy, Economics and Climate Change*, 1992).

Fitzharris and Garr (1995) conclude that changes in precipitation patterns resulting from climate change could result in increased hydroelectric production in the South Island of New Zealand, arising at more useful times of the year. Lettenmaier *et al*. (1992) estimate that a 2–4°C warming in Northern California would reduce snow accumulation and shift peak runoff from spring to winter. This would result in a closer match between runoff and peak power demand in the region, but, on the other hand, water supply would become less reliable. More efficient reservoir management alone could not mitigate the additional risk of floods, and additional reservoir storage for flood flow would be needed (Lettenmaier and Sheer, 1991). Such a response might increase the potential for hydroelectric production during floods but affect the availability of the reservoir system to meet other demands, such as those for irrigation. Where water storage is dominated by snowmelt rather than by reservoirs, river basins are likely to be more sensitive to temperature shifts than to hydrological changes (Lettenmaier and Sheer, 1991).

11.6.3.1.2. Wind

Wind energy depends in part on the temperature gradient from low latitudes to high (Grubb and Meyer, 1993). Estimates of potential climate change based on general circulation models have suggested that the high latitudes should warm relatively more than the tropics (IPCC, 1990a). By itself this would reduce the temperature gradient and global wind resources. The wind resource at some sites, however—such as Altamont Pass in California—is determined largely by a combination of local topography and location, so that the resource there might display less direct sensitivity to changes in global circulation patterns. For existing wind installations, a change in the direction of the prevailing wind also could have a significant effect, depending on the orientation of the array.

Established wind energy systems are potentially vulnerable to changes in the local wind regime because wind energy flux varies with the cube of wind velocity (Cavallo *et al*., 1993). Windspeeds above average contribute disproportionately to wind generator output. A changed frequency of higher windspeeds would have the greatest impact on output. Baker *et al*. (1990) analyzed long-term wind records at good but undeveloped wind sites and estimated that a 10% change in wind speeds could change wind energy yields by 13–25%, depending on the site and season. In general, if climate change manifests itself as greater variability in wind speeds, then wind energy production will tend to magnify this variability. An increase in wind resources would cause a disproportionately large increase in energy capture, while a decrease would cause a disproportionately large decrease.

Air density decreases with increasing temperature (Cavallo *et al*., 1993), but an average increase of several degrees at a developed site should reduce output by at most 1–2%. In the high latitudes, where global warming might be more pronounced, air density and hence output could decrease to a greater extent (IPCC, 1990a).

11.6.3.1.3. Other renewable energy sources

Solar thermal and photovoltaic (PV) energy systems are dependent on local conditions (Radesovich and Skinrood, 1989; De Laquil *et al*., 1993). Systems that concentrate sunlight, using either mirrors to reflect it or lenses to refract it, require direct sunlight. Increases in humidity, haze, or cloudiness reduce the effectiveness of concentrating systems (Kelly, 1993). Global climate change may alter cloud regimes, leading, possibly, to more clouds and less direct solar radiation (Enquête Kommission, 1991). Cloudiness has recently increased over Europe, North America, India, and Australia as a whole (IPCC, 1990a) but has decreased in Southern Australia and in the Sahel (CSIRO, 1992b).

Flat-plate PV systems utilize both direct sunlight and diffuse light scattered by clouds or humidity. Electricity from a flat-plate system in a region with relatively poor conditions might be 40% lower than that from an identical system in a region with excellent conditions (Zweibel and Barnett, 1993). This range is probably much greater than the difference produced by a gradual change in climate. Photovoltaic cells lose about 0.5% of their efficiency per °C above their rated temperature (Kelly, 1993).

Ocean energy systems comprise a variety of technologies, including tidal barrages, wave energy systems, and ocean thermal energy conversion (OTEC). There are few plans to develop ocean energy systems, though their use might grow in the longer term. It would be essential to take account of projected sea-level rise over the very long design life of tidal barrages (UK Climate Change Impacts Review Group, 1991). Wave energy resources at any particular site depend on global wind patterns to generate waves, nearshore winds that affect wave size, and nearshore seabed conditions that affect the refraction and reflection of waves (Cavanagh *et al*., 1993).

Geothermal resources may be affected by a change in precipitation patterns where the steam resource depends on an aquifer recharged by surface water or precipitation. An assessment of the potential effects of climate change in New Zealand (Mundy, 1990) suggests that increased rainfall could increase the recharge of groundwater for most geothermal fields.

11.6.3.2. Impacts on the Value of Resources

Several renewable energy resources, especially PV systems, often have high value because they are dependable when demand for energy is highest. Some changes in climate could shift demand peaks or change energy yields, thus altering the value of affected systems.

The use of some renewable energy resources must be balanced against other potential uses. For example, in hydroelectric systems, energy production may compete with demands for water to provide wildlife habitat, irrigate crops, maintain navigation, and support recreation. In coastal ocean energy systems, energy production may compete with demands to protect wildlife habitat or support recreation. Climate change could lead the public to place greater value on the nonenergy uses of these resources, leading to a decline in energy production.

11.6.3.3. Impacts on Performance

Climate change could affect renewable energy technologies by changing the performance and the degree of damage incurred during extreme weather events. Adapting to these impacts could alter operation and maintenance costs. The economic impacts, however, are likely to be much lower than those deriving from climate mitigation policies designed to promote renewable energy. The main climate impacts are:

- For hydroelectric systems, precipitation patterns and climatic impacts on vegetation of the watershed could affect rates of siltation and reservoir storage capacity.
- Dust, insects, or ice can reduce wind energy production by about 8% (Lynette, 1989; Lynette and Associates, 1992). Light rainfall may clean the blades and increase energy yields by up to 3%, but heavy rain can reduce energy output by increasing turbulence (Baker *et al*., 1990).
- Severe weather (tornadoes, hurricanes, snow, and ice) can damage wind machines (Jensen and Van Hulle, 1991), though the use of variable-speed wind turbines shows great promise for reducing this source of vulnerability (Lamarre, 1992).
- Soiling of the reflective surfaces of heliostats through dust can reduce energy capture by solar thermal systems by up to 8% when there is little rainfall (Radesovich and Skinrood, 1989). Efforts to reduce system costs have led to the development of larger heliostats that are more susceptible to wind damage.
- Soiling also affects PV systems (Goossens *et al*., 1993). Moisture from storms or dew, lightning strikes, overheating, and voltage surges from cloud-induced transients can cause damage to electronic components (Conover, 1989; Kelly, 1993; Boes and Luque, 1993; Smith, 1989). An increase in peak windspeed or in the frequency or severity of storms would require the structures necessary to support PV collectors to be strengthened (Kelly, 1993).
- Ocean energy systems would be susceptible to storm damage (Cavanagh *et al*., 1993).

11.7. Need for Future Assessments

Many elements of the industry-transportation-energy system are sensitive to extremes of climate rather than average conditions. The impacts of many variables also are specific to geographical regions. If work on the potential impact of climate change on the industry, energy, and transportation sectors is to develop beyond a simple identification of sensitivities, then it will be necessary to generate climate scenarios that cover a wider range of climate variables, including extreme events, and refer to changes at the regional as well as global levels. The capacity to produce such scenarios does not yet exist. Several types of climate impact in the industry, energy, and transportation sectors appear to merit further research.

Developing Country Studies

A number of comprehensive studies of the impacts of climate change on developed countries have been published. Extending this type of work to cover a wider range of developing countries, which are likely to be more sensitive to climate, should have a high priority. Agroindustries merit special attention, given the dependence of many developing countries on agriculture and derivative sectors. Very few studies have been conducted that trace the indirect effects of changes in agricultural activity on associated agroindustries. With a few exceptions, only casual inferences have been drawn concerning the secondary impacts of agricultural productivity on industrial output and employment. This problem can be addressed through economic models that characterize the relationships between agriculture and industrial activity. The linkages between marine ecosystems, fisheries, and fish-processing industries similarly need to be assessed.

Studies at the System Level

Much of the climate sensitivity exhibited by the industries examined in this chapter arises not because of the direct impacts of climate on an activity but because of interdependence *between* activities through either climate-sensitive markets or the use of raw materials and resources that are themselves climate sensitive. Studies that increase understanding of these interdependencies and the indirect consequences of climate change throughout the economic system are an essential complement to studies that focus on specific sectors and activities.

Energy Demand

There is a need for studies that assess the impacts of climate change on energy demand and the impact of GHG mitigation measures within a unified framework. The adoption of mitigation measures such as energy efficiency, renewable energy, or biomass production may influence the vulnerability of the energy system to climate change while, at the same time, the direct impacts of climate change may influence the degree of mitigation action required to attain specific GHG emission objectives. No studies addressing this topic have been identified.

Also, although there have been many studies of the impact of climate on energy demand, there is still considerable uncertainty about the possible links between the adoption of new air-conditioning systems and climate change, particularly in temperate climates where the use of air conditioning is currently marginal.

Transportation

More assessment of impacts on transportation infrastructure and operations is needed. It is especially important to extend studies to developing countries and countries with economies in transition. Issues other than submergence as a result of sea-level rise should be considered. The impacts of temperature, precipitation, and extreme events on both infrastructure and operations should be included.

Transportation issues should be addressed within the wider framework of changes in human settlement patterns. The question of the impacts of climate change on regional transportation systems via the redistribution of population and economic activities has been neglected. There is a need to develop and refine an assessment methodology by adapting existing transportation models. Eventually, such models would be employed to evaluate scenarios of regional growth derived from climate change impact studies of migration, agriculture, industry, and other sectors to determine changes in transportation demand and impacts on transportation networks.

Adaptation

The literature referring to industry, energy, and transportation focuses largely on sensitivities and impacts and is weak on questions of adaptation. There are some areas where research on adaptation could be appropriate. Infrastructure associated with some large-scale renewable energy projects, transportation systems, and buildings has a very long lifetime. It may be necessary to anticipate climate change by assessing how demand for facilities may be affected by climate in the long-term and how climate might influence technical aspects of design. The development of climate guidelines is necessary for the construction and location of coastal structures such as seawalls, harbors, jetties, piers, and causeways that have long lives (Hameed, 1993). Such guidelines would also assist with the design of new buildings, particularly with respect to their energy use characteristics. Improved monitoring of coastal zones, covering sea level, tidal and wave patterns, weather, marine ecosystems, coral reefs, coastal geomorphology, and sedimentology also is required (Crawford, 1993).

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